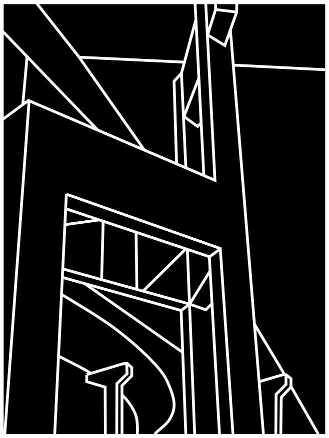
PROJECT SUMMARY REPORT 2974-S

TRAFFIC NOISE MEASUREMENTS AT FM 3009 GREENFIELD VILLAGE SUBDIVISION, CITY OF SCHERTZ, TEXAS

Thomas E. Owen, Michael T. McNerney, Hong Mao, Erika D. Muñoz, Roxanne Alamos, M. J. Larsen, and Daniel Ayala



CENTER FOR TRANSPORTATION RESEARCH
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16. Abstract

Objectives of the studies were to: (1) determine by quantitative measurements and computer simulation modeling the effectiveness of the noise barriers; (2) determine the traffic noise intrusion through openings in the barriers at streets entering the residential areas; (3) conduct a community opinion survey to characterize the subjective effectiveness of the noise barriers; and (4) compare field measurements with computer-modeled results. Project efforts resulted in the development and application of a source-referenced noise level measurement and spatial contouring method for characterizing noise intrusion through the barrier openings. Similar measurements were used in comparing noise barrier insertion loss measurements with measurements at locations without the noise barrier. A mail-distributed opinion survey questionnaire was developed that resulted in a 60% return from the 289 residences in the subdivision. The overall results of the opinion survey indicated that 69% of the primary receiver residences had positive opinions concerning the effectiveness of the noise barrier installation.

Field measurements indicated the insertion loss along the continuous noise barrier to be 8–12 dB in the yards of the primary receivers adjacent to FM 3009. Noise intrusion through residential street openings in the barrier panels reduced the insertion loss measured in the yards of the primary receiver by 4–6 dB, depending on the specific primary receiver yard layout.

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Research Project 7-2974
Sound Wall on FM 3009 in San Antonio

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN
and the

INSTITUTE FOR RESEARCH IN SCIENCES AND ENGINEERING
THE UNIVERSITY OF TEXAS AT SAN ANTONIO

November 1996
Revised: August 1997

IMPLEMENTATION RECOMMENDATIONS

The findings of this research project confirmed the effectiveness of the noise barriers in the study area in reducing noise levels at adjacent properties; quantified the degradation in the effectiveness of noise barriers as a result of openings for residential streets; documented the effectiveness of the noise barriers from a perspective of adjacent property owners; and validated the accuracy of noise levels predicted by computer modeling.

Since the study revealed no discrepancies in the effectiveness of noise barriers or associated computer modeling, there is no implementation necessary in these areas. However, these results and the results of the public opinion survey provide credible information that can be used to respond to associated inquiries from the public, and to prepare presentations for the public during public meetings/hearings and noise workshops.

Studies of a similar nature could be conducted for each of the various types of noise barriers constructed by TxDOT to provide a reference for designers of subsequent noise barriers. Also, a study will be required to validate the noise levels and effectiveness of noise barriers predicted by the new FHWA approved Traffic Noise (computer) Model that was not available at the time this study was conducted.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Prepared in cooperation with the Texas Department of Transportation

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Geologist, Environmental Section

The University of Texas at Austin

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Professor, Mechanical Engineering

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

A traffic noise abatement barrier was constructed during the summer of 1995 in the area of Greenfield Village Subdivision on FM 3009 in the City of Schertz, Guadalupe County, Texas. In planning and implementing the noise barrier project, a comprehensive traffic noise analysis was conducted by the Texas Department of Transportation (TxDOT) during the summer of 1994 in the nearby residential areas affected by vehicular traffic on FM 3009. Measured noise levels and traffic noise predictions based on STAMINA 2.0 computer simulations for existing 1994 and projected 2005 traffic flow conditions were analyzed and clearly indicated the need for traffic noise abatement measures in the area. The STAMINA 2.0 computer model data, combined with practical site layout conditions and cost-effectiveness constraints, formed the basis for the final TxDOT design and location of the noise barrier along FM 3009.

The TxDOT preconstruction noise analysis for FM 3009 was based on noise levels measured at thirty-three locations in residential yards and at other accessible locations adjacent to the roadway between the cross streets of Eli Whitney on the north end of the subdivision and Webster Drive on the south end (barrier zone length: approximately 670 m). Twelve test stations were located on the east side of FM 3009 and twenty-one test stations were located on the west side of FM 3009. Four residential entry streets are on the east side and three residential entry streets are on the west side of FM 3009. Site schematic drawings obtained from the San Antonio District Office provided coordinate layout information on the preconstruction noise measurement locations and the postconstruction locations of the noise barrier panels and their construction details along the FM 3009 right-of-way boundaries.

Traffic noise on FM 3009 was simulated by TxDOT at the thirty-three receiver locations using STAMINA2.0. These model studies showed that the 1994 preconstruction noise levels were predictable from the observed traffic flow and provided estimates of traffic noise levels for projected future traffic loads on FM 3009. STAMINA 2.0 was also used to predict the reduction in 2005 design-year traffic noise for representative noise barriers on each side of FM 3009. As determined by this study, the 1994 noise levels ranged from 61 dBA to 66 dBA (east side) and

61 dBA to 64 dBA (west side). The projected 2005 design-year noise levels without a barrier were in the range of 66 dBA to 73 dBA. The Federal Highway Administration (FHWA) noise abatement criterion for residential areas is 67 dBA, with the corresponding TxDOT criterion slightly more stringent at 66 dBA. Therefore, the 2005 projected traffic noise observed on the east side of FM 3009 required that noise mitigation be considered.

The TxDOT traffic noise analysis postulated the use of noise barriers on the east and west sides of FM 3009 as a means of mitigating the 2005 design-year noise levels to meet the noise abatement criteria for impacted residences. Using practical design specifications for a 3.7-m high barrier on the east side and a 4.6-m high barrier on the west side of FM 3009, the STAMINA 2.0 computer simulation results showed that the traffic noise levels projected for the 2005 design year would be reduced to 60.4 dBA (east side) and 63.0 dBA (west side). Exceptions to such reductions include four receiver locations located near the street openings in the barriers. At the street opening having the highest intrusive noise, Will Rogers Drive, the projected noise levels were 66 dBA (three receivers) and 67 dBA (one receiver). Based on these findings and on the 10-year projection period involved, the noise mitigation effectiveness of the noise barriers was considered to be cost justifiable and reasonable. Construction of the planned noise barrier was carried out as part of a larger-scale project already underway to recondition and widen FM 3009. The noise barrier installation was completed in July 1995 at an approximate cost of $25,000 per primary receiver residence.

1.2 RESEARCH STUDY OBJECTIVES

TxDOT simulations of the traffic noise barriers pointed out that the weak points in the noise mitigation process were the street openings into the residential area. Thus, the principal objective of this research study was to determine, from field measurements, the traffic noise intrusion at the entry street openings and adjacent receivers, and to compare the results with those predicted by computer simulation modeling. Since many of the primary receiver residents were involved in initiating the TxDOT noise mitigation project, a supplemental goal was to conduct a community opinion survey on the subjective effectiveness of the noise barriers. Four specific objectives were defined for the study:

(1) Determine, by quantitative field measurements and analysis, the effectiveness of the traffic noise barrier recently constructed on FM3009 at the Greenfield Village subdivision in the City of Schertz, Texas.

(2) Determine the impact of the noise barrier openings at the residential entry streets on the noise reduction effectiveness of the FM 3009 traffic noise barriers on each side of FM 3009.

(3) Conduct and evaluate an opinion survey of the area residents to characterize the differences between noise annoyances experienced before and after construction of the FM 3009 traffic noise barrier.

(4) Compare field measurements with noise levels predicted by computer simulated modeling.

1.3 TXDOT COORDINATION AND COLLABORATION WITH THE CENTER FOR TRANSPORTATION RESEARCH (CTR) AT THE UNIVERSITY OF TEXAS AT AUSTIN

The reported project efforts were planned and conducted by a traffic noise research team at The University of Texas at San Antonio (UTSA) and coordinated with related computer simulation studies performed by the Center for Transportation Research (CTR) at The University of Texas at Austin. This work was closely coordinated with the TxDOT San Antonio District Office, including priorities of the project goals and objectives, review and approval of the field test plan, review and approval of the opinion survey questionnaire, and concurrence on protocols for contacting residents of the field site area. Progress on these various project tasks was documented and distributed to TxDOT and CTR.

1.4 SUMMARY OF WORK ACCOMPLISHED

1.4.1 Noise Barrier Effectiveness

Field measurements were conducted to demonstrate the noise reduction capabilities of a continuous section of the 4.6-m high noise barrier on the west side of FM3009. Noise levels measured behind this barrier were quantitatively compared with noise levels measured in an adjacent open field to show that the noise in the adjacent receiver yards was abated by more than

8 dBA. This result is consistent with the mitigating effects predicted by the TxDOT noise analysis conducted prior to constructing the noise barriers.

1.4.2 Noise Intrusion through Street Openings

A specialized field measurement procedure was developed to measure and evaluate traffic noise intruding through the street openings into the residential area. The results of these tests, performed at four different openings in the noise barriers, indicated that the 8–12 dBA noise abatement provided by the continuous barrier was compromised by 3 dBA to 6 dBA, depending on the width of the opening in the barrier. The sound level contours derived from measurements in the entry streets and yards of the residences within approximately 60 m of the barrier openings were consistent with those predicted by computer simulation models of the areas in question. Traffic flow on FM 3009 was observed during the morning and evening rush hours to indicate a typical rush-hour flow of 1,100 vehicles/hour, including approximately 4% heavy trucks. Based on these observations, the 1996 traffic load on FM 3009 was estimated to be 12,600 vehicles per day.

1.4.3 Community Opinion Survey

The community opinion survey on traffic noise from FM 3009 before and after constructing the noise barriers was responsive and informative. A favorable consensus expressed by those residents located immediately adjacent to FM 3009 indicated that the barrier was significantly effective in reducing the traffic noise experienced prior to construction. Residents located at greater distances from the barriers reported a less noticeable difference in the before-and-after traffic noise levels, although this result must be weighted by the associated lower magnitude of traffic noise and its reduced subjective impact at greater distances from the roadway. Overall, a substantial majority of the area residents expressed satisfaction with all aspects of the noise barriers.

1.4.4 Comparison of Field Measurements with Computer Model Predictions

The traffic noise measurements recorded at several different locations along FM 3009 provided numerous opportunities for comparing sound level measurements in the field with sound levels predicted by computer modeling. The field measurement locations included: (1) an open field adjacent to the roadway that had no noise barrier; (2) a residential area located behind a continuous noise barrier wall; and (3) several street entrances into the residential area having noise barrier openings ranging in width from 5.2 m (utility alley) to 25.6 m (Will Rogers Drive). With the exception of one of the street openings (Cyrus McCormick Street), where the ground elevations differed significantly from the roadway elevation (and thus were not available for use in the model), the field measurements and computer simulated sound level results were within ±1 dB when the observed traffic densities were used in the model. The computer model used for these predictions was "SoundPLAN," a comprehensive noise modeling program containing the same FHWA-certified traffic noise calculation algorithms as STAMINA in one of its modules, and having capabilities for taking into account ground topography, sound diffraction around the edges of finite-length barriers, and reflections from structural surfaces in the vicinity of the receivers in another of its modules. From modeling runs using both of these simulation modules with a site representation constrained to the limitations of the FHWA STAMINA computer model, the simulated results using SoundPLAN and SoundPLAN emulation of STAMINA were essentially identical. Furthermore, for the noise measurements obtained at the open field site and at the site behind the continuous noise barrier (both sites accurately representable by STAMINA), the measured and model-predicted sound levels were within ±1 dB when the observed traffic density was used in the model.

CHAPTER 2. FM 3009 FIELD SITE

2.1 GREENFIELD VILLAGE SUBDIVISION, SCHERTZ, TEXAS

The field test site was located in the Greenfield Village Subdivision on FM 3009 in the City of Schertz, Guadalupe County, Texas. The subdivision contains twenty-one streets, seven of which provide access into the subdivision from FM 3009. The streets entering the subdivision from FM 3009 include Cherrywood, Cyrus McCormick Street, Eli Whitney, Patrick Henry, Silvertree, Webster Drive, and Will Rogers Drive. The subdivision is approximately 850 m long and extends back 520 m on the west side and 275 m on the east side. There are 289 residences in the subdivision. A layout map of the Greenfield Village Subdivision is presented in Figure 2.1.

Construction to widen and improve FM 3009 in Schertz, Texas, began in 1993 and was completed in the summer of 1994. The construction increased the number of lanes on FM 3009 from two to five, including a continuous center-turn lane. The width of the former roadway's pavement averaged 10.7 m, whereas after construction the pavement width was approximately 23 m. This expansion made significant changes in the proximity of many of the adjacent houses to the roadway. For example, one of the houses adjacent to the right-of-way at the Cyrus McCormick Street entrance was located about 15.2 m from the traffic lanes on the former roadway. The new roadway width decreased the distance to 7.6 m. Figure 2.2 shows the newly completed roadway and sections of the noise barrier along FM 3009 in the Greenfield Village Subdivision.

Traffic noise was measured primarily in the residential areas adjacent to FM 3009 from Webster Drive to Eli Whitney, a distance of approximately 670 m. Traffic noise measurements were also conducted on selected residential streets. Sound level meters were located as close as 8 m from the FM 3009 roadway and at distances into the subdivision entry streets of about 60 m from the roadway. Typical traffic loads on FM 3009 before widening the roadway were approximately 10,000 vehicles/day.[1] TxDOT traffic counts derived from midday observations in August 1993 prior to specifying and constructing the noise barrier were, on average, 490 autos/hr and 35 trucks/hr. The present-day traffic load on FM 3009 was measured to document the traffic noise measurements performed during peak traffic conditions occurring in the mornings and afternoon. These data, when weighted by a representative 24-hour traffic flow profile, yielded an estimated daily traffic load of 12,600 vehicles/day (summer 1996).

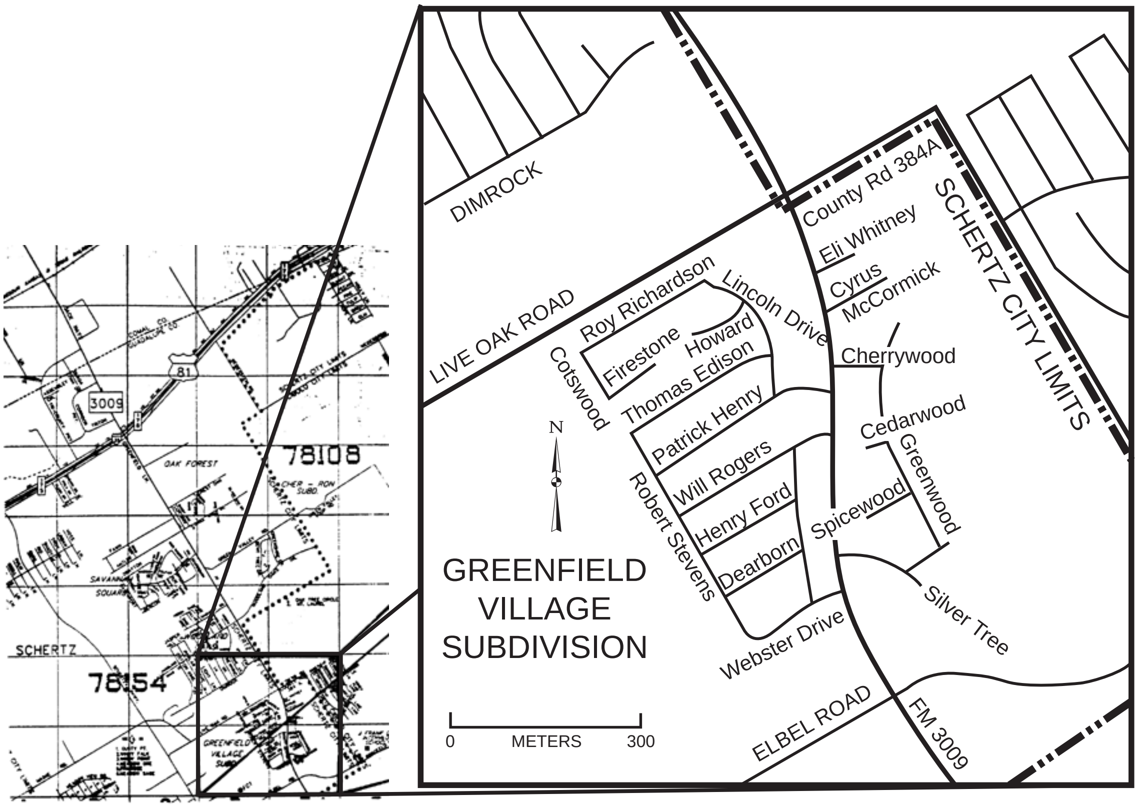

Figure 2.1 Area map of Greenfield Village Subdivision in Schertz, Texas. North-south artery is FM 3009. Traffic signal is at FM 3009 and Elbel Road.

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[1] Personal communication with Carl Wenzel, TxDOT, San Antonio District, San Antonio, Texas.

Figure 2.2(a) North view at Webster Drive

Figure 2.2(b) South view at Cyrus McCormick

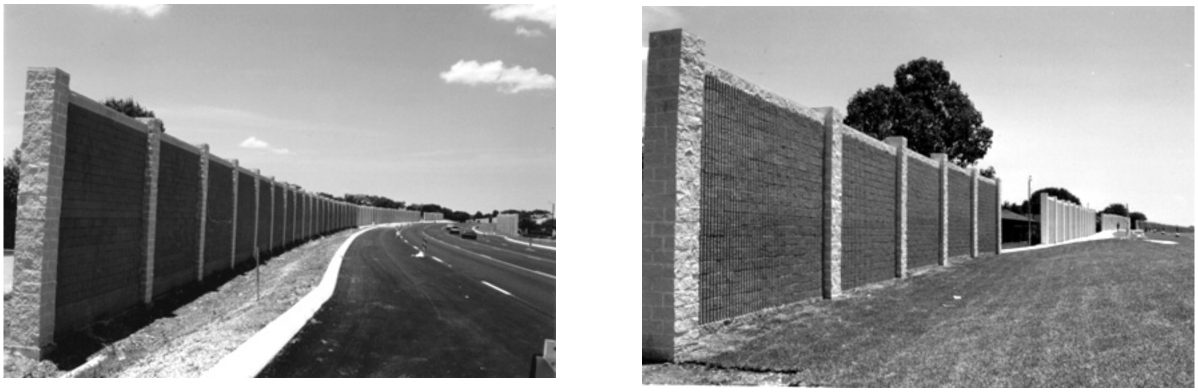

Figure 2.2(c) Barrier elevation difference at Eli Whitney

Figure 2.2(d) Barrier structure and surface texture

Figure 2.2 Traffic noise barriers on FM 3009 at Greenfield Village Subdivision, Schertz, Texas (summer 1995)

2.2 TRAFFIC NOISE BARRIERS

In an effort to reduce the excessive noise caused by increasing traffic on FM 3009 at the Greenfield Village Subdivision, TxDOT constructed two separate barriers along FM 3009. The east side of the subdivision received a 3.7 m high and 460 m long barrier, whereas the west side received a 4.6 m high and 365 m long barrier. The effectiveness of the noise barriers was most beneficial to those residences located immediately adjacent to the roadway, designated as the "primary receivers." Along the east side of FM 3009 there are four street openings with twelve primary receivers. The west side of FM 3009 has three street openings with twenty primary receivers, of which eighteen have rear home entries facing the roadway. A total of thirty-two primary receivers are located adjacent to the FM 3009 roadway noise barriers.

There are a total of seven barrier sections established along FM 3009; three are located on the west side and four are on the east side. They are situated immediately along the original right-of-way, since no additional right-of-way was required. The barriers are not continuous along the roadway because of the openings required for access into the residential area. Each section of the barrier wall is a 10.2 cm thick reinforced masonry panel approximately 3 m wide; the wall is built to the required 3.7 m–4.6 m height on a grade beam foundation with drilled shaft piers. Each 3-m panel is supported by 0.6-m x 0.6-m vertical pillars set into the concrete foundation. Front and back surfaces of the panels are textured and colored for desirable appearance and good weatherability.

CHAPTER 3. COMMUNITY TRAFFIC NOISE OPINION SURVEY

3.1 SURVEY PURPOSE AND SCOPE

The residents of Greenfield Village Subdivision, Schertz, Texas, were surveyed by mail to gather information on the effectiveness of the traffic noise barrier recently constructed on FM 3009. The principal purpose of the survey was to determine whether the affected area residents felt that the noise barrier was beneficial and, specifically, whether the noise disturbances caused by large trucks were adequately reduced. The mail-distributed questionnaire, its methodology, and its response data are presented in Appendix A.

The survey questionnaire contained nine questions designed to elicit the opinions of area residents with respect to traffic noise annoyances experienced before and after construction of the barrier. Figure 3.1 shows the layout of the subdivision, which has a total of 289 residences (not all shown). Preliminary review of the 171 opinion survey responses received from these residences revealed that the significant responses concerning FM 3009 traffic noise came from those residents living within approximately 180 m of the FM 3009 centerline. Accordingly, the community survey was restricted to those residents located within 180 m of the centerline.

3.2 SURVEY RESULTS AND DISCUSSION

The residents located immediately adjacent to the noise barriers on each side of FM 3009 are defined as *primary receivers.* All other residences located laterally behind the noise barriers along FM 3009 and within 180 m of the highway centerline are defined as *secondary receivers.* This selected area includes approximately 130 residence addresses with 132 known independent residents. In the primary receiver area there are thirty-two residences and known residents. We received a total of twenty-five survey replies from this area, representing a 78% response rate. In the secondary receiver area there are 98 residences with 100 residents. We received a total of sixty-four survey replies from this area, representing a 65% response rate. We received a total of eighty-nine survey replies from both receiver areas, representing an overall response rate of 67%.

The layout of the Greenfield Village Subdivision shown in Figure 3.1 illustrates the path of FM 3009, the residential area entry streets, the noise barrier locations, and the locations of approximately 130 residences within the 180-m boundary limits. Figure 3.1 also shows the area distribution of the receiver responses to the principal question of the survey: Question No. 6*: Has the barrier reduced the noise of large trucks?* ☐ *Yes* ☐ *No.* Sixty-two percent of all the respondents stated affirmatively that the barrier reduced the noise of large trucks. Sixty-nine percent of the primary receiver respondents gave affirmative responses to this question.

Figures 3.2 through 3.6 summarize the receiver responses to the remaining survey questions. The opinion responses are presented separately for the primary and secondary receiver categories. For example, in Figure 3.2 the responses to Question No. 6 show that 69% of the primary receivers consider the noise of larger trucks to be reduced. This result is clearly a positive indication of the effectiveness of the noise barrier, since the primary receivers experience the greatest impact of the traffic noise. Although only 36% of the secondary receivers stated that the noise of the large trucks was reduced, this lower response is also influenced by the lower subjective impact of traffic noise on receivers located up to 180 m away from FM 3009. In these outer areas, the noise of larger trucks may not be noticeably annoying either with or without the noise barrier. The affirmative responses of the primary receivers in reply to the other “yes/no” questions shown in Figure 3.2 indicate that the primary receivers are strongly aware of the FM 3009 traffic load and that they appreciate the generally beneficial effects of the noise barrier. The secondary receiver affirmative responses to these “yes/no” questions are all lower (by about one-half) than the primary responses, indicating further that a “no” answer may also imply less awareness of FM 3009 traffic noise as a problem.

Replies to Question No. 3: *Has there been a noticeable increase in the number of trucks on FM 3009?* ☐ *Same* ☐ *More Medium* ☐ *More Heavy*, summarized in Figure 3.3, showed a consensus that there are now more medium and heavy trucks traveling on FM 3009 than before the noise barrier was constructed. The replies to Questions No. 6 (Figure 3.2) and No. 3 (Figure 3.1), in combination, provide good evidence that, even with a perceived increase in truck traffic, the subjective noise environment in the Greenfield Village Subdivision has been improved significantly by the barriers. The favorable responses by both primary and secondary receivers to Question No. 5 related to the general residential noise environment, as summarized in Figure 3.4 for indoor and outdoor conditions, further support this conclusion.

Question Number 6:
"Has the barrier reduced the noise of large trucks?"

"Yes" responses	
Primary receivers	69%
Secondary receivers	36%
All receivers	**62%**

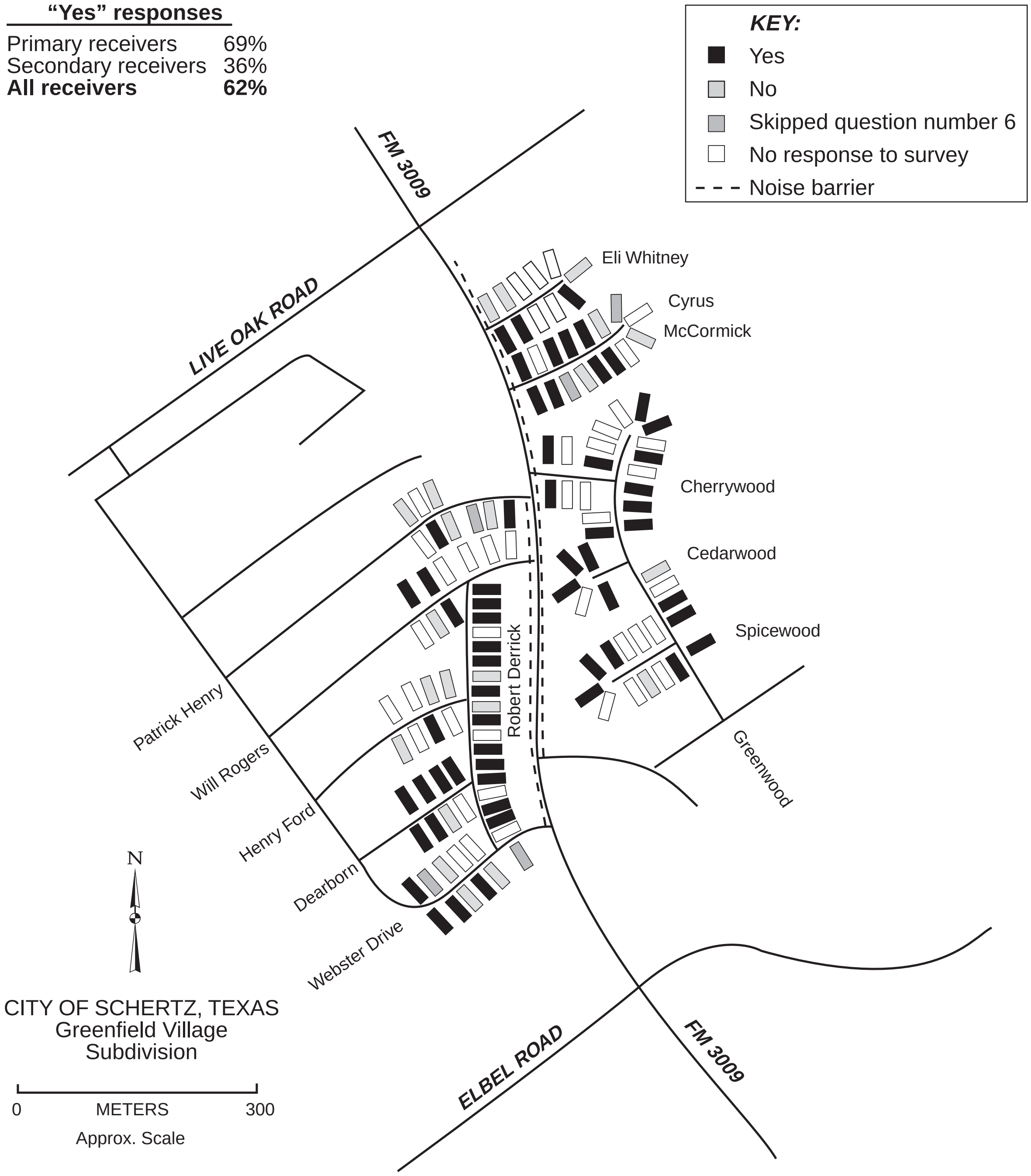

Figure 3.1 Residential area of Greenfield Village Subdivision, designating receiver residences used in the traffic noise opinion survey

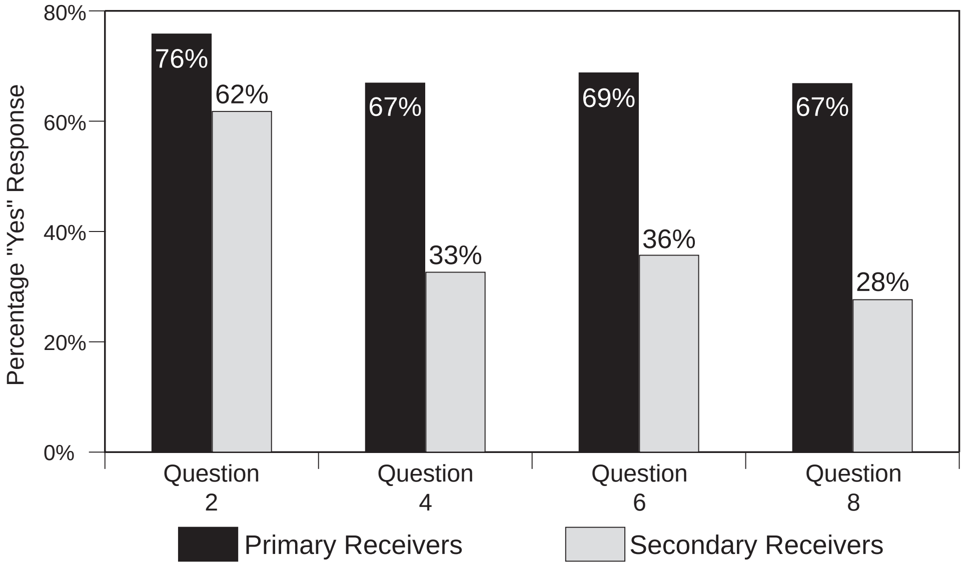

Figure 3.2 Opinion survey "Yes" responses on traffic flow conditions on FM 3009 Including:[1]

Question No. 2:	*Has the amount of traffic on FM 3009 increased?*
Question No. 4:	*Have you noticed a difference in the amount of traffic noise since the barrier has been in place?*
Question No. 6:	*Has the barrier reduced the noise of large trucks?*
Question No. 8:	*Has the barrier improved the appearance of the residential area?*

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[1] Complete survey questions are presented in Appendix A, Figure A-1.

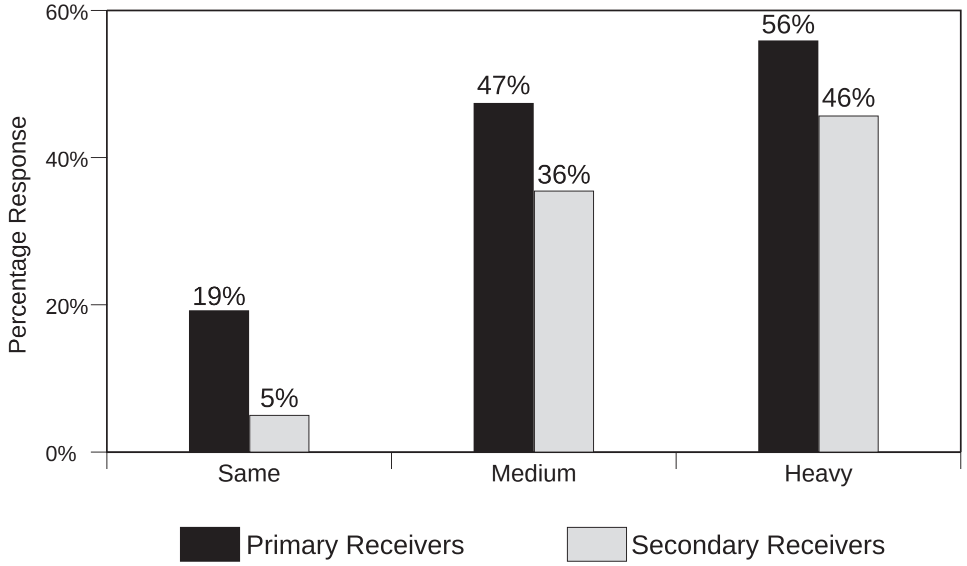

Figure 3.3 Opinion survey responses on traffic flow conditions on FM 3009 in reference to:[2]

Question No. 3: Has there been a noticeable change in the number of trucks on FM 3009?

Answer choices: About the same / More medium-size trucks / More heavy trucks.

For Question No. 7 (Figure 3.5), respondents indicated that traffic noise is most noticeable during the daytime and evening periods (6:00 a.m.–10:00 p.m.); for Question No. 8 (Figure 3.2), a majority of respondents indicated that the noise barriers have improved the appearance of the residential area; and for Question No. 9 (Figure 3.6), 68% of the primary receiver respondents experienced no interruptions in their daily activities as a result of traffic noise on FM 3009.

The favorable consensus in response to all of the survey questions concerning the traffic noise barrier on FM 3009 supports the conclusion that the barrier is effective in abating traffic noise. Individual write-in comments, also solicited in the survey questionnaire but not analyzed in detail, provided additional favorable support of this conclusion (see Appendix A).

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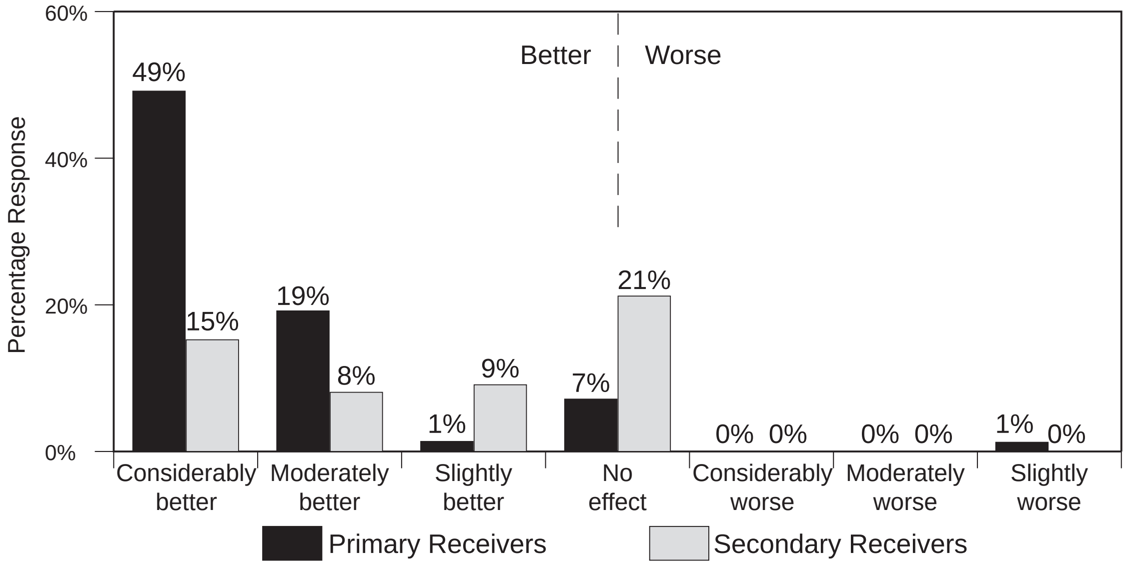
[2] Complete survey questions are presented in Appendix A, Figure A-1.


(a) Indoors

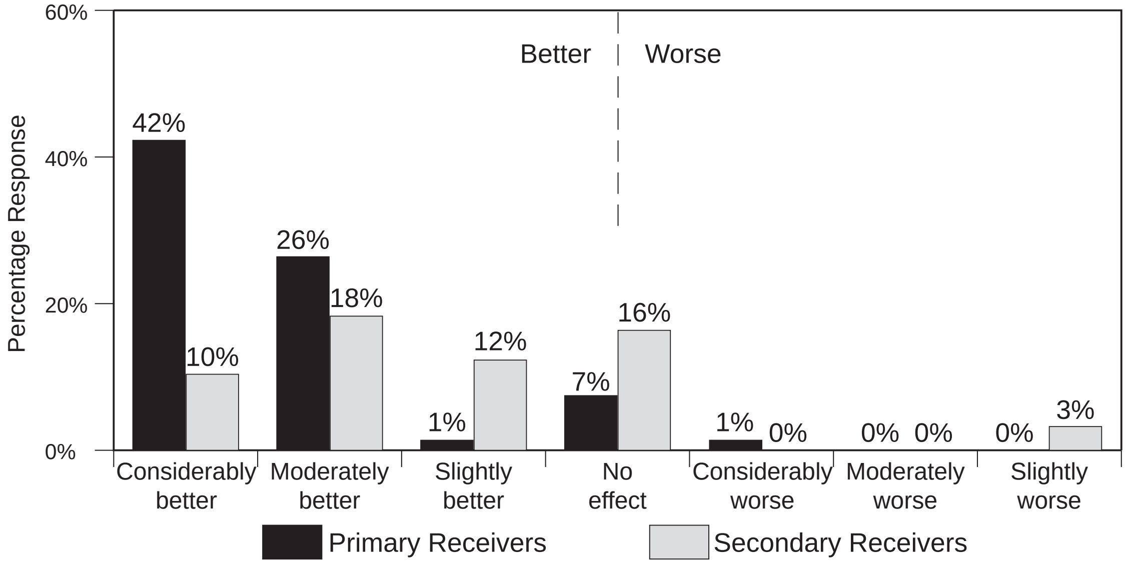

(b) Outdoors

Figure 3.4 *Opinion survey responses on traffic flow conditions on FM 3009 in reference to:*

Question No. 5: *What effect has the noise barrier had on the traffic noise around you home? (a) Indoors/(b) Outdoors*

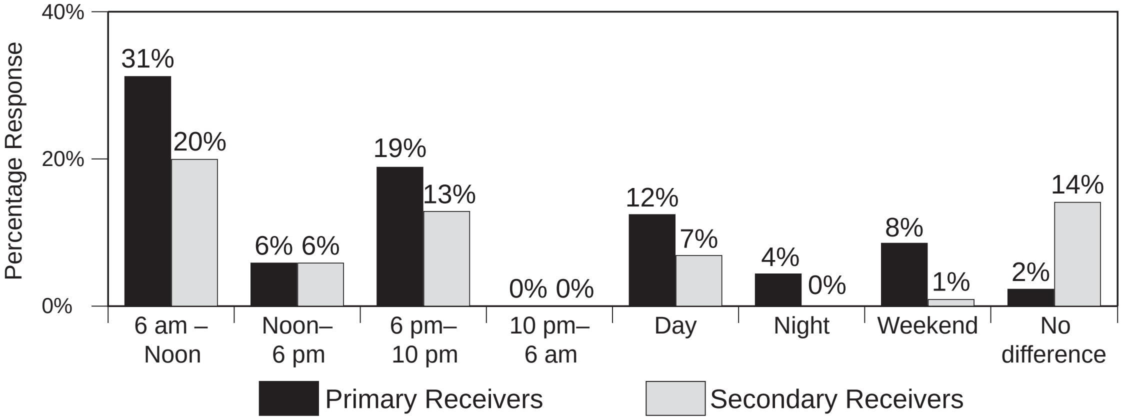


Figure 3.5 Opinion survey responses on traffic noise conditions in reference to:[3]

Question No. 7: When is the traffic noise most noticeable?

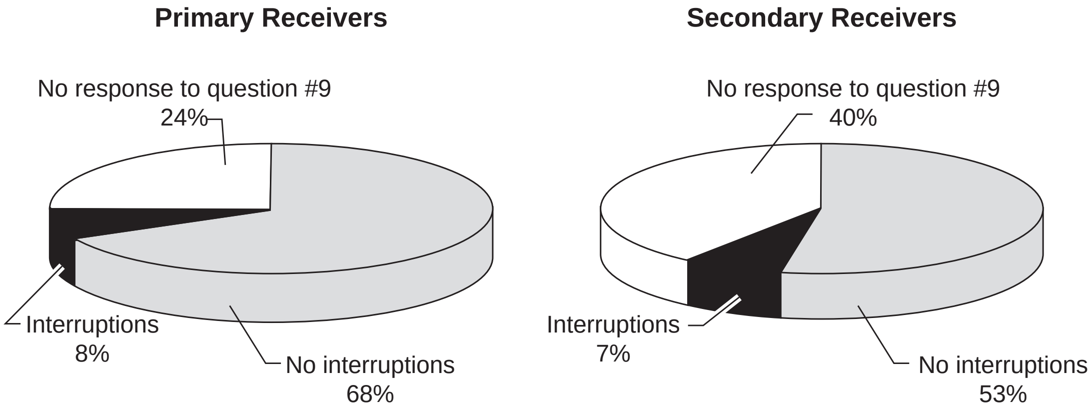


Figure 3.6 Opinion survey responses on effectiveness of noise barrier in reference to:

Question No. 9: Has the traffic noise on FM 3009 ever annoyed or interrupted your daily activities?

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[3] Complete survey questions are presented in Appendix A, Figure A-1.

CHAPTER 4. TRAFFIC NOISE MEASUREMENTS AND COMPUTER MODELING

4.1 NOISE INTRUSION AT ENTRY STREET OPENINGS

An important project goal was to collect and evaluate quantitative experimental measurements of traffic noise intruding through openings in the noise barriers at streets entering the residential area. The technical approach used in these measurements was one in which a number of spatially distributed noise levels were recorded at the opening in the barrier and at distances farther into the residential street area. The observed noise readings were then processed to permit contours of constant noise level to be drawn, showing the approximate distribution of the intruding noise in the yards and along the street. These results were also compared with noise level measurements taken at a continuous section of the noise barrier to show the increase in noise permitted by the street openings. Further, by comparing similar noise intrusion levels and contours for two or more street openings having different widths, the general effects of the width of the street opening were determined. A literature survey was conducted to determine the state of the question regarding traffic noise measurements at street openings (no references were found on this specific subject) and to develop an up-to-date bibliography on traffic noise and its abatement. Appendix D lists recent and key background references on general traffic noise problems/technology and community noise exposure (supplemental to references in Appendix A), as well as technical papers on noise barrier analysis, performance, and modeling.

The spatial distribution of noise measurements described above requires a total of 25–30 microphone stations extending 40 m–50m into the residential area of interest. This requirement presents a problem in obtaining uniformly related noise level data for contour mapping, since only four microphone sensors were available and the traffic flow volume on FM 3009 was variable during the time required to collect the desired number of noise measurements. This problem was resolved by restricting the noise level measurements to the times of greatest traffic flow and dedicating one microphone station nearest to FM 3009 as a fixed-location noise level reference for each group of four microphones used to collect simultaneous noise level readings. Thus, by recording noise level averages for a time period of 10 minutes for each group of four microphone locations (one microphone in each group always at the reference location) and allowing 8 minutes (typical) to prepare each group for the next sequence of measurements, fifteen spatially distributed measurements and one reference position (i.e., five groups) could be recorded in 90 minutes. The morning and afternoon traffic rush hours were found to last about 90 minutes (6:30–8:00 a.m. and 5:00–6:30 p.m.). Thus, we measured the first half of the noise intrusion at a particular street opening in the morning and the second half in the afternoon. During each of the 90-minute field recording sessions, we also used a video camera to provide a continuous visual record of the traffic flow on FM 3009.

Field procedures developed for conducting the traffic noise intrusion measurements included preparing special-purpose site layout drawings, taking position measurements for each microphone station, conducting microphone calibration tests at the beginning and end of each 90-minute session, downloading digital noise level data recorded by each microphone, recording descriptive field notes on nontraffic-related background noises, videotaping traffic flow, and photographing the noise barrier street opening and the residential site conditions in the test area at the time of measurement. To ensure accurate and efficient field operations, specific duties were assigned to each member of the six-person project team.

4.1.1 Instrumentation and Equipment

The planned traffic noise measurements were made practical by the use of four programmable digital sound level meters designed specifically for industrial noise level and noise exposure surveys. In addition to the sound level meters, a portable laptop computer was used in the field to program the microphone measurement time intervals and to transfer the digital memory records for each four-microphone observation sequence to magnetic diskette files. A video-cassette camera was used to obtain unattended, permanent video records of the traffic flow occurring during noise level measurement sessions. The instrumentation used for the traffic noise measurements is described below.

Digital Sound Level Meters: The instruments of primary importance for traffic noise measurements of FM 3009 were digital sound level meters capable of recording and storing in memory a time history of the measured sound level and internally processing the average sound level and other noise level parameters. The particular instruments used for this purpose were Metrosonics Model db-3100 Metrologger programmable sound level meters equipped with a microphone, a portable microphone calibrator, and a software programming disk (Metrosoft 3100) for use with an IBM-compatible computer (either desktop or laptop). Four instruments of this type were obtained on loan from TxDOT's San Antonio District, as was the software disk (IBM-compatible computers were available at UTSA).

Prior to their use, the Metrosonics dB-3100 instruments require that the operating program first be installed using the software programming disk. The Metrosoft 3100 program can then change the operating settings of the instrument to (1) provide data recordings controlled by an internal real-time date/time clock, (2) adjust the sound averaging time window, (3) adjust the data recording time period, and (4) change the settings for numerous other measurements/data parameters related to sound level peak values and threshold levels related to noise exposure dosage.

Technical Specifications of Metrosonics dB-3100 Metrologger

Microphone:	Metrosonics ¼-inch-diameter ceramic type microphone with 1-meter long cable and connector
Sound Level Range:	40 dB to 140 dB
Dynamic Range:	100.0 dB (analog/digital)
Amplitude Linearity:	± 0.7 dB
Amplitude Resolution:	± 0.1 dB
Sound Signal Detector:	True RMS
Sound Sampling Rates:	Slow — 16 samples/sec Fast — 64 samples/sec
Peak Range:	28 dB

Applicable Instrument
Standards: Type 2: ANSI S 1.4 - 1983
ANSI S 1.25 - 1978
IEC 651; IEC 804

User Programmable Parameters:

Frequency Response: A - weighted
C - weighted

Avg. Response Time: Slow — 1 sec. / Fast — 0.125 sec.
Real Time Clock: Date, time

Data Recording Schedule: Date, time - turn on
Record time duration before turn-off

Time History Data: Interval Time: Hrs., Min., Sec
Processed Values: L_{avg}, L_{max}, L_{pk}

Data Display: 3 ½ - digit LCD

Operating Temperature
Range: - 20ºC to + 60ºC

Battery: 9V alkaline

Typical Battery Life: 40 hrs. @ 25ºC (min. 24 hrs. continuous)

Size and Weight: 3 in. x 4.8 in. x 0.9 in.; 12 oz

Additional Equipment: Additional equipment and supplies used to conduct the traffic noise field measurements included:

Video Camera: Panasonic VHS Camcorder Model AG-188

Laptop Computer: Toshiba T4400C 386 IBM compatible

Tripod Mounts: Velbran C X 440 (four each for microphones)
Slik 550 G-FL (one each for camcorder)

Steel Measuring Tape: 30.48 m

Metal Marker Pins: Eight each

Microphone Extension Pole: 4.5 m (aluminum, telescoping)

Camera Supplies: Blank videotape cassettes (eight)
Photographic film

4.1.2 Microphone Positions and Field Layout

The procedures followed for measuring traffic noise intruding through the street openings were developed by reviewing the TxDOT schematic drawings of the FM 3009 roadway construction project and by inspecting the field site. The schematic drawings presented complete details on the new FM 3009 roadway and the noise barrier (constructed in July 1995). These drawings also showed the locations and layouts of the residential entry street for lateral distances of approximately 60 m beyond the FM 3009 right-of-way. The general locations of the residential houses that existed at the time that the schematic drawings were prepared were confirmed by the site inspection visits. Additional houses have been constructed since 1994 on the entry streets located on the west side of FM 3009.

The FM 3009 project site coordinates used in the TxDOT schematic drawings (Texas State Plane Coordinate System NAD–1983) were used to locate the roadway and the noise barrier panels relative to the centerlines of the residential streets (all entry streets exhibit some degree of curvature). A secondary coordinate system was devised for convenient layout of the microphone measurement stations along the residential streets and in the yards of the houses where measurements were recorded. For this purpose, a line following the north curb of the residential street was used as the noise intrusion direction, with lines perpendicular to this curb used to locate the microphone stations and the set-back distances of the north-side houses, garages, fences, etc. Similarly, a line following the south curb was used to locate the microphone stations and houses, garages, fences, etc. on the south side of the residential street. Microphone stations were also located on the centerline of the residential streets. The microphone stations defined by these street-oriented coordinates were later translated to FM 3009 project site coordinates for use in the computer simulation model studies and in other comparisons. Figure 4.1 shows the sound level meters and laptop computer equipment used in the field measurements.

The locations of the microphones used at each street opening site were selected at the time of the measurements. The actual locations of the houses, vegetation, and vehicles (parked in the street and in driveways) precluded the microphone stations from being specified using only the site schematic drawings. Spacings between the microphone stations in the noise intrusion direction were selected to provide a noise decrement of about 2 dB between stations, based on the assumption that the intrusion noise obeyed a cylindrical wave (line source) geometrical spreading law. On this basis, the microphone spacing used in these field measurements was 9.1 m along the curbs and centerline of the street. Because of various obstacles, the microphone spacings differed slightly from 9.1 m in the yards and driveways of the houses.

(a) Metrosonics dB 3100 sound level meters

(b) Video recording of traffic flow

(c) Downloading noise measurement files to laptop computer

(d) Log sheet records of microphone layout positions and extraneous noise

Figure 4.1 Instrumentation for traffic noise measurements

4.1.3 Source-Referenced Sound Level Measurements

A critical requirement for generating valid noise intrusion contour maps is to achieve a common reference for each group of four microphone readings with respect to the traffic flow source conditions. This was accomplished by always designating the first microphone station on the FM 3009 oncoming traffic corner of the residential street as the reference noise measurements position. By maintaining one of the microphones in each group of four simultaneously recorded noise levels at this position, each group of average sound level records could be linearly shifted in magnitude (dB scale) to coincide with the average sound level of the first (or any other) recorded group. For the particular noise measurements at several locations on FM 3009, the typical source reference adjustments for the different microphone groups were in the range of -4.7 dB to +3.3 dB to account for differences in the prevailing traffic flow. With four sound level meters available for the field measurements, one microphone unit must always be located at the reference position, while the other three are free to be placed at other stations in the measurement grid.

In using this method, each of the microphone units was calibrated at the beginning of the measurement session so that their individual readings could later be referenced to a standard noise reference level. Microphone calibration adjustments are discussed in Appendix C. Each unit was thereafter retained as an associated sensor system consisting of a particular microphone element and its electronics package, in order to preserve their correct calibration as a unit. For measurements at the FM 3009 field site, the microphone and electronic unit pairs were assigned identifications of M-1, M-2, M-3, and M-R and marked with stick-on labels. The unit marked M-R was always used at the reference position.

Source-referenced sound level measurements are capable of maintaining the readings of any group of three movable microphones in accurate reference relative to any other group of three microphones, independent of variations in the traffic flow conditions during the sequential operating time intervals of the groups. Constraints on this process require that the noise observation time interval be sufficiently long to include the typical mix of auto and truck vehicles (typically 10 minutes or longer) and that the sound propagation and sound reflection and scattering conditions in the test area remain essentially unchanged for all of the microphones group measurements to be combined through the referencing process. These conditions were satisfied in the FM 3009 field measurements, even though half of the microphone groups were recorded in the morning and the other half recorded in the afternoon.

4.1.4 Field Data Collection Procedures

The procedures required for collecting traffic noise intrusion measurements and other noise level readings at the FM 3009 field site included:

(1) City and private property access arrangements in advance of field measurements: Telephone contacts were made with the primary receiver residents and with other residents of the Greenfield Village Subdivision in those cases where we needed to access their yards or fence gates. Several days in advance of the field tests, we contacted occupants to describe the planned activities and time schedule. Permission was obtained from all residents contacted. Where microphone stations were located in the streets, especially as unattended equipment setups, arrangements with the City of Schertz were advisable. Caution flags and the presence of project field personnel were sufficient to alert motorists on the residential streets to the microphone tripods in the street. No microphone stations were required in the FM 3009 roadway.

(2) Advance site inspection: Advance inspection of the specific field test locations provided guidelines for the measurements, although exact locations of the microphone stations were selected after arrival at the site on the day of the measurements. Preliminary observations of traffic flow on FM 3009 indicated that the preferred times for traffic noise measurements were during the morning and evening rush hours.

(3) Microphone station positions: With schematic drawings available showing the street openings, noise barrier panels, the adjacent houses, and the street layout dimensions and curvatures, the secondary coordinate system described earlier using street curbs as references was used to locate the selected microphone stations. For this purpose, a 100-foot tape and wire marker pins were used to record the microphone positions. These coordinates were recorded on a layout sketch of the street. The set-back distance of the main front surfaces of the houses were also measured and recorded, as were the positions of vehicles and other equally large sound

reflecting obstacles (boats, privacy fences, etc.). Two project members were assigned the task of documenting the field coordinates of each microphone station and other site layout and noise environment information. A log of nontraffic sound interferences (nearby residential street traffic, house air conditioner operating noise, aircraft, etc.) was also maintained. Description, time of occurrence, microphone stations active, source location of disturbing noise if known, and disturbance duration time were listed. These notes were later used to edit the microphone noise records to gate out significant nontraffic noise disturbances.

(4) Traffic flow video records: One member of the project team was assigned the task of setting up and operating the video camcorder to record traffic during each noise measurement session. The camcorder was set up to give an appropriate field of view documenting the vehicles traveling in each lane of FM 3009 and in observing vehicle positions relative to selected background position-fixing landmarks. Additional videotapes were used as needed to record the traffic conditions continuously throughout the noise measurement sessions.

(5) Sound level meter preparations: The four Metrosonics dB 3100 sound level meters were equipped with fresh batteries and programmed for 10-minute recording time intervals by an IBM-compatible laptop computer. The time of day entered into the sound level meters was identical in all units and accurately synchronized with the wristwatch of the person assigned to perform the microphone programming and data downloading task.

(6) Initial sound level meter calibration: The Metrosonics portable sound reference calibration source was used to calibrate each sound level meter by recording a 20-second calibration file at the beginning of the noise measurement session. These data were downloaded and stored in a reference file on floppy disks. To ensure correct calibration, the microphones of the sound level meters were identified and marked so as to be always associated with their particular electronic meter units.

(7) Sound level measurements: The microphones were mounted on camera tripods at a height of 1.2 m above ground; the electronics unit was also attached to the tripod to form a portable noise measurement unit. The portable noise measurement units were placed at their designated locations (the reference unit always located at the same position) and activated to begin recording at their programmed time. At the end of the programmed operating time interval

(as signaled by the assigned data program task person), the three moveable noise measurement units were moved to their next recording station. By means of a hand signal by one of the field team members handling these units (including the reference unit), the sound level meters were manually activated to record a second 10-minute traffic noise file. Because these second recording sequences could not be programmed in advance in the Metrosonics dB 3100 sound level meters, they were manually activated at a specified time and stopped manually after 10 minutes had elapsed.

(8) Noise data transfer to files: At the end of the two 10-minute data recordings, described in Step 7, the electronic units were collected and their data files downloaded to a floppy disk with accurate identification of their ID numbers. Each unit was then reprogrammed to automatically start the next 10-minute noise recording interval. The electronic units were then returned to their respective microphone-tripod assemblies and moved to the next data recording station.

(9) Complete field data measurements: The actions in Step 7 were repeated until all of the planned traffic noise measurements were collected and downloaded to disk files.

(10) Final sound level meter calibration: At the end of the noise data collection session, the portable sound calibrator unit was again used to record a 20-second microphone calibration data file.

(11) Field data verification check: All data files recorded and downloaded in the field were checked to confirm noise data content and files for each designated microphone station before leaving the field site.

(12) Sound level meter battery life: A battery life consumption record was compiled from the data file durations and new batteries installed after 20 hours of battery operation.

(13) Office procedures: After each field outing, the traffic noise data files were returned to the office and listed in hardcopy form using the standard Metrosoft 3100 program data output formats. These outputs present time-based plots of the average noise levels for each 2-second time increment of the 10-minute observation intervals of each sound level meter file. Numerical values of the average traffic noise (and other derived noise data parameters) for the 10-minute time interval were computed by the Metrosoft program. The 10-minute average noise levels,

calibration data, data file numbers, and microphone station coordinates were then entered into a standard spreadsheet (see Appendix C). The sound level readings were adjusted to compensate for their individual microphone calibrations; these adjusted readings were then normalized (translated linearly in dB) to the reference sound level so that they could be used in comparing and mapping the various noise levels obtained at the microphone stations.

4.1.5 Traffic Flow Measurements

Traffic flow on FM 3009 was recorded during each of the field data recording sessions. Traffic was videotaped to obtain a continuous and permanent record of the vehicles traveling on FM 3009 during each 10-minute noise recording interval. These video records were analyzed later after each field outing to determine the number of vehicles traveling in each lane, their classification as either automobiles or trucks, and their average speeds. The methodology used for these traffic flow determinations is presented in Appendix B, together with tabulations of the traffic flow rates and other data relevant to the traffic load on FM 3009 at the times the noise measurements were made.

Figures 4.2 through 4.4 summarize the observed traffic flow on FM 3009 interpreted from the videotapes. These data depict the auto and heavy truck traffic over the 10-minute time intervals during the various traffic noise measurements. The field measurements were conducted during 2-hour morning and evening rush-hour periods when traffic was heaviest. Figure 4.2 shows typical views of the traffic taken from the videotapes. Figures 4.3 and 4.4 depict the traffic flow analysis obtained from videotapes recorded on four different days in May 1996. The vehicle counts shown in these figures represent: (a) the combined automobiles and (b) the combined autos and trucks traveling in both directions of FM 3009 converted from the 10-minute observation intervals to average traffic flow in vehicles/hr. The number of trucks in each 10-minute interval is proportional to the vertical separations between the plotted lines. Because of the selective rush-hour observation times and the limited number of observation days, a more representative estimate of traffic flow in FM 3009 is given by the average of all data collected. Thus, for the periods observed, the typical rush-hour traffic on FM 3009 is:

Morning Rush Hour	(6:30–8:30 a.m.)	1060 Autos/Hr.	50 Trucks/Hr.
Evening Rush Hour	(5:00–7:00 p.m.)	1136 Autos/Hr.	29 Trucks/Hr.
	Combined Average	1096 Autos/Hr.	40 Trucks/Hr.

Traffic speed was determined from the video recordings using the method described in Appendix B. Automobiles and trucks on FM 3009 were found to travel at essentially the same speed, averaging 80–88 kph in all of the observations.

The traffic flow rates determined from the rush-hour observations have been extended in an appropriate manner to estimate the present-day traffic load on FM 3009. For this purpose, the combined average morning and evening rush-hour vehicle flow rates were scaled down to represent four periods of traffic activity during the 24-hour day. These traffic-load conditions and the estimated daily traffic load are summarized in Table 4.1.

Figure 4.4(d) illustrates the postulated traffic density profile derived from the observed rush-hour averages and vehicle mix to estimate the present-day (1996) traffic load on FM 3009 at the Greenfield Village Subdivision. A 5% annual increase in the total estimated 1996 traffic load of 12,601 vehicles/day will result in a total traffic load of 19,550 vehicles/day at the end of the year 2005.

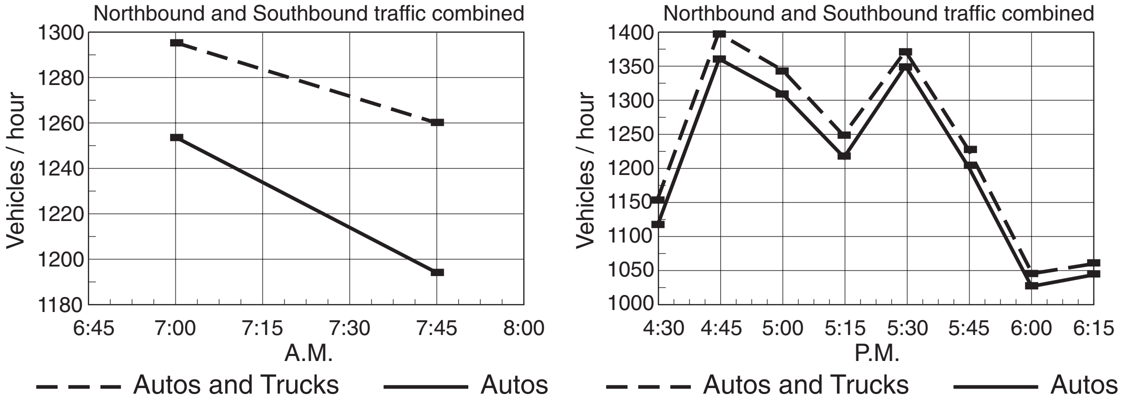
(a) *Camera at Will Rogers*

(b) *Camera at Cherrywood Street*

(c) *Camera at Cyrus McCormick Street*

(d) *Heavy truck acceleration noise test*

Figure 4.2 Sample video records of traffic flow on FM 3009 (summer 1996)



(a) Morning – May 17, 1996 (Tallied manually)

(b) Evening – May 17, 1996

(c) Morning – May 20, 1996

(d) Evening – May 20, 1996

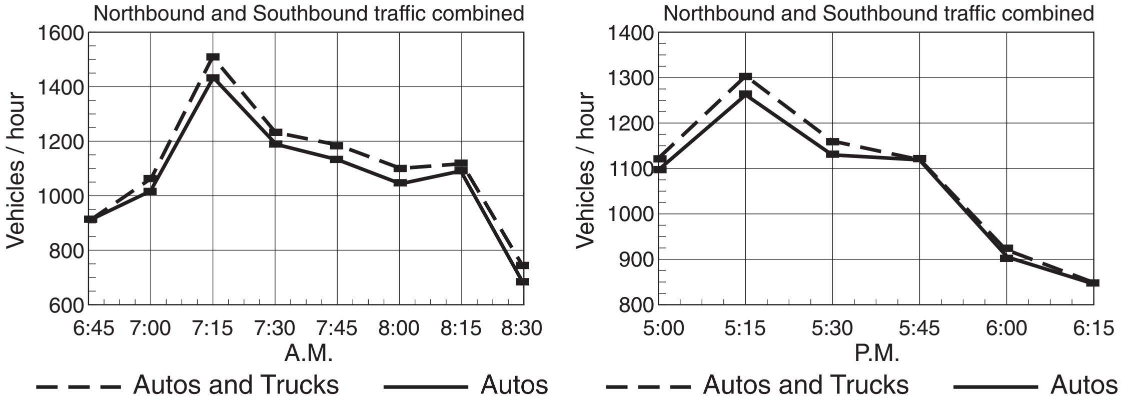
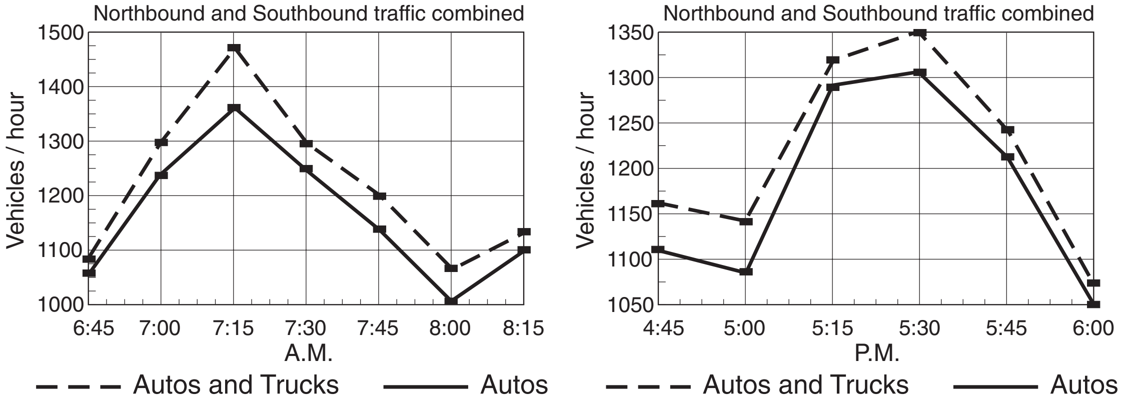
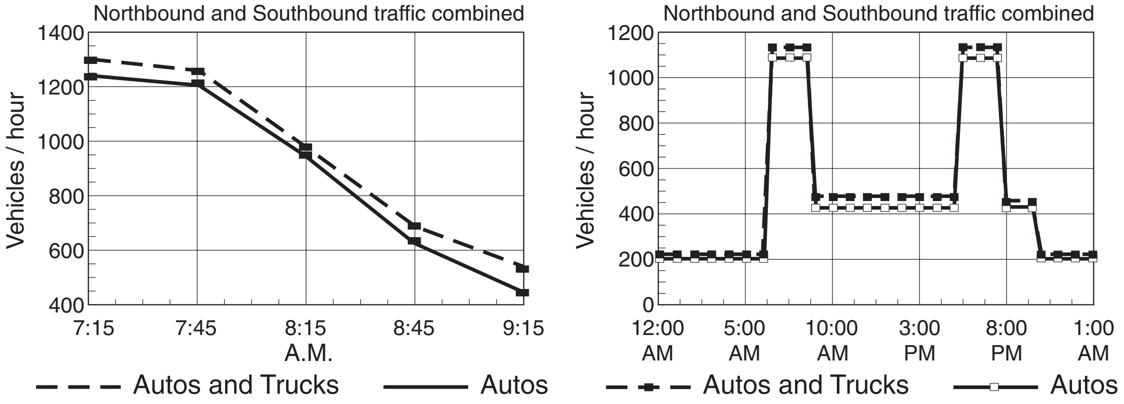


Figure 4.3 *Morning and evening traffic load on FM 3009 from video recordings (measured over 10-minute time intervals—Summer 1996)*



(a) Morning – May 22, 1996

(b) Evening – May 22, 1996



(c) Morning – May 23, 1996

(d) Estimated Daily Traffic Profile – May 1996

Figure 4.4 Morning and evening traffic and estimated daily traffic load profile— FM 3009 at Greenfield Village Subdivision

4.1.6. Computer Simulation Model

The experimental field studies of the traffic noise barrier on FM 3009 were supplemented by computer simulation modeling using the commercial software program SoundPLAN. This traffic noise computer simulation program was developed in Germany by Braunstein & Berndt International (Robert-Bosch-Str. 5; D-71397 Leutenbach, Germany) and is distributed in the U.S. by Navcon Engineering Network (701 W. Las Palmas Dr., Fullerton, California 92835). Access to the software for use on the present project was provided on a temporary basis by Navcon Engineering Network. Training with SoundPLAN was provided to UTSA project personnel and to CTR personnel by C. R. Todd of PMK, Inc., 1420 W. Mockingbird Lane, Suite 400, Dallas, Texas 75247.

Table 4.1 Estimated traffic load on FM 3009 — May 1996

Time Period/Day	Scaled Flow	Vehicle Flow Rate	Number of Autos	Number of Trucks	Total Vehicles
Rush-Hour (6:30 - 8:30 a.m. + 5:00 - 7:30 p.m.)					
2 X 2.5 hr.	100%	1096 Auto/hr.	5,480	--	5,680
2 X 2.5 hr.	100%	40 Trucks/hr.	--	200	
Mid-Day (9:00 a.m. - 5:00 p.m.)					
8 hr.	40%	1096 Auto/hr.	3,507	--	3,827
8 hr.	100%	40 Trucks/hr.	--	320	
Evening (7:30 p.m. - 10:00 p.m.)					
2.5 hr.	40%	1096 Auto/hr.	1,096	--	1,146
2.5 hr.	50%	40 Trucks/hr.	--	50	
Night (10:00 p.m. - 6:30 a.m.)					
8.5 hr.	20%	1096 Auto/hr.	1863	--	1,948
8.5 hr.	25%	40 Trucks/hr.	--	85	
Totals/day			**11,946**	**655**	**12,601**

SoundPLAN, which has a modular format, is capable of simulating traffic noise, railroad noise, aircraft noise, and industrial noise. It utilizes site representative geographical database inputs, including terrain contours, outdoor noise barriers, and appropriate building structures.

Output information is in the form of single-point sound level tables and maps, noise level distribution contour maps, and other diagrammatic representations of noise fields and analysis reports. The program is designed to implement national standards for road, rail, and industry noise for the U.S., Germany, U.K., Austria, and Scandinavia. Included in the SoundPLAN software is an implementation of the FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108). This is the same model implemented by STAMINA 2.0 and widely used by TxDOT and other transportation organizations in the U.S. The program was run on an IBM 386 computer equipped with 8MB memory and a math coprocessor. Graphics output information requires plotters or printers compatible with HPGL-2 graphics language.

Figure 4.5 illustrates the general data and design inputs and the computational sequence of SoundPLAN. With the assistance of PMK, the site layout data for FM 3009 were directly transferred into the program from TxDOT digital schematic drawing files in the MicroStation CAD format. These drawings contained layout information on the roadway and residential streets, the locations of houses known at the time of the drawings, and ground elevation contours relevant to the widening construction requirements of the roadway. Detailed ground elevation contour information was not available for the residential streets and private properties. Traffic vehicle flow rate and noise barrier locations and specifications were entered manually and were changeable to represent various traffic noise conditions and noise barrier effects to be studied. The locations, dimensions, and barrier openings at the residential streets entering into the subdivision were accurately represented using information obtained from the final site construction schematic drawings.

SoundPLAN was utilized in this study to provide model predictions of traffic noise abatement effects associated with the noise barrier panels on FM 3009. These predictions are only approximate, since they are based upon simplifications of actual sound propagation effects and contain limited details representing the ground elevation contours and houses in the Greenfield Village Subdivision. The FM 3009 project noise levels could have been modeled by representing each individual lane of traffic. However, without developing specific traffic flow and vehicle mixtures for each lane, the traffic was modeled as two lanes (one in each direction), carrying the accurately observed vehicle flows in each direction. The number of lanes that

SoundPLAN can model is limited only by the computer platform memory and computing capability.

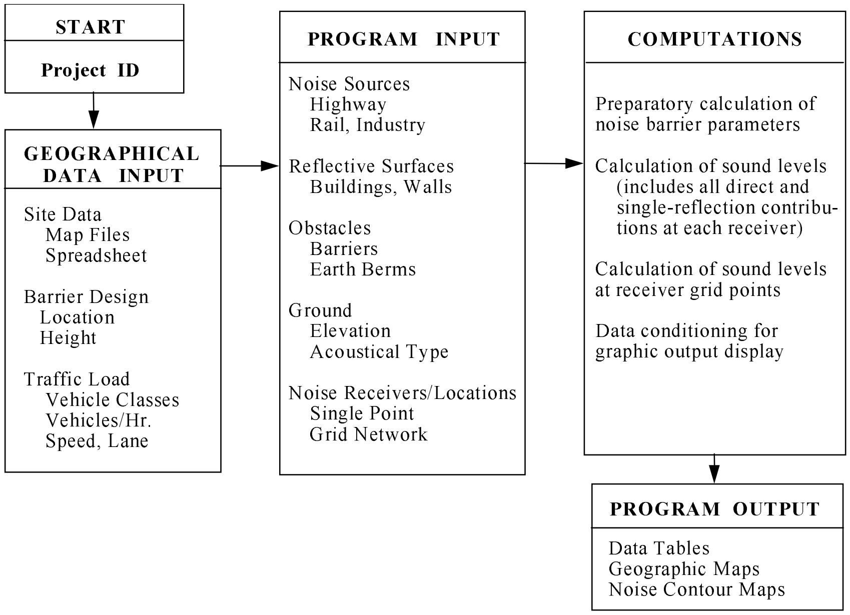


Figure 4.5 Descriptive flow diagram of SoundPLAN computer simulation program

4.1.7 Will Rogers Drive — Measurements and Results

Will Rogers Drive enters the west half of Greenfield Village Subdivision from FM 3009 at a location where there is a noise barrier approximately 67 m in length north of the entrance and a noise barrier approximately 260 m in length south of the entrance. The height of these barrier panels is approximately 3.8 m above the FM 3009 road surface. The 67 m length of the Will Rogers Drive barrier is interrupted at its midpoint by a 4.6 m wide service alley entrance.

The opening in the noise barrier at Will Rogers Drive, approximately 25.6 m wide, is the largest of the four noise barrier street openings at the site—42% wider than the smallest opening at Cherrywood Street. At a distance of approximately 32.3 m on the opposite side of FM 3009, the noise barrier is approximately 4.7 m high and serves as a traffic noise reflector (no street openings) along the roadway for distances of about 137 m north and south of Will Rogers Drive. The elevation of Will Rogers Drive is approximately the same as the road surface on FM 3009.

Figure 4.6 shows several views of Will Rogers Drive, illustrating the noise barrier opening and the residential environment into which the traffic noise intrudes. Figure 4.6(a) shows the 25.6 m wide barrier opening in the foreground and four houses on the north side of the street. Noise measurements were performed in the yards and in the street area visible in Figures 4.6(b) and 4.6(c). Figure 4.6(c) also shows a view of FM 3009 through the noise barrier opening at Will Rogers Drive, indicating two vehicles parked on the north side of the street. The 4.7 m high noise barrier on the opposite side of FM 3009 is in the background. Figure 4.6(d) shows the side yard of the primary receiver residence on the north side of the street opening. Will Rogers Drive has a nearly circular curve with a radius of curvature of approximately 90 m.

(a) Noise barrier opening at entrance

(b) Residential houses and street curvature

(c) Parked vehicle sound obstacles

(d) Primary receiver Yard—North side

Figure 4.6 Will Rogers Drive at FM 3009

Traffic noise levels were measured at forty-two receiver stations located in the yards of the houses and along the curbs and centerline of Will Rogers Drive for a distance of approximately 65 m from the barrier opening. At the time of the measurements, the two vehicles shown in Figure 4.6(c) were parked at a distance of 15–23 m inside the barrier opening. The reference microphone was stationed on the north curb of Will Rogers Drive on a line joining the ends of the noise barriers on each side of the street. Three other microphones, operated as a sequentially repositioned group, were located at positions selected to provide measurement stations oriented approximately perpendicular to the centerline of the street at distance intervals of 9.1 m along the centerline. Typically, five receiver stations formed each perpendicular line and were set up and operated according to the field procedures described earlier. One-half of the forty-two receiver stations were recorded during a 2-hour time period in the morning (north side, 6:40–8:40 a.m.) and the second half of the stations were recorded in the afternoon (south side, 4:40-6:40 p.m.), with both periods corresponding to the times of heaviest traffic on FM 3009. Microphone calibration tests were recorded at the beginning and end of each measurement session. Detailed field data records of the microphone station layout positions and average sound level readings recorded during the measurement time intervals are presented in Appendix C.

Traffic flow conditions on FM 3009 averaged 1,058 autos/hour and 32 trucks/hour during the two measurement sessions on Will Rogers Drive. Figure 4.3 presented earlier shows the traffic flow time history during the morning and afternoon data recording periods. The traffic on FM 3009 exhibits morning and afternoon rush hours of automobile traffic and a relatively steady volume of commercial truck traffic throughout the day.

Figure 4.7 shows the results of the traffic noise intrusion measurements on Will Rogers Drive. The measured noise levels were adjusted for their individual microphone calibrations measured during the data collection times and normalized to a common traffic load condition on FM 3009 using the average noise level readings at the reference microphone station. The constant noise level contours shown in Figure 4.7 are analytically derived for interior spaces between the microphone locations oriented perpendicular to the street (solid contour segments) and are estimated and drawn manually in the areas close to the houses where more complex scattering occurs from localized obstacles and other irregularities in the area (dashed contour segments). Nonlinear interpolation of the normalized sound level readings was applied using a cylindrical wave spreading law relationship for microphone stations oriented along lines parallel to the noise intrusion direction (away from the noise barrier opening). Linear interpolation was used to map the noise level contours between microphone stations located at common distances from the barrier opening. The nonlinear interpolation law was devised and validated by analyzing the experimental microphone readings recorded on the centerline of the street.

The noise level contour patterns shown in Figure 4.7 are reasonable representations of the sound propagation and scattering conditions along Will Rogers Drive. The noise abatement effects at locations immediately behind the barriers (approximately 9 dBA or greater reductions) are evident. The increased and decreased noise levels in the front and rear proximities, respectively, of the two parked vehicles are clearly evident and consistent with the vehicle locations along the street. The stronger intrusion noise levels along the south curb of Will Rogers Drive are caused by the sound-confining effects and reflections from the long brick masonry side of the house located within about 4–6 m of the curb, as shown in Figure 4.6(b) left side.

Noise levels below 56.5 dBA (average) were not contoured because of interference from nontraffic background sound sources (residential air conditioners, etc.). The quietest background noise floor at the most distant microphone stations, when no close traffic was present on FM 3009 and no other identifiable sound sources were noticeable, was in the range of 48 to 50 dBA.

Figure 4.8 shows a corresponding noise level contour map for Will Rogers Drive derived using the SoundPLAN computer simulation program. The traffic noise model parameters used to generate these noise level contours included:

(a) use of the actual project site coordinates (Texas State Plane Coordinate System; NAD-1983) to locate the roadway lanes, noise barriers, street layout, existing houses, and the specific microphone positions used in the field measurements;

(b) use of the traffic flow vehicle mix observed during the field measurements on Will Rogers Drive with adjustments in the vehicle count to make the modeled traffic noise level the same as the noise level recorded at the reference microphone position; and

(c) interpolation of the noise level contour lines derived from the simulated noise intrusion pattern using the same methods applied to the contour maps of the experimental field measurements.

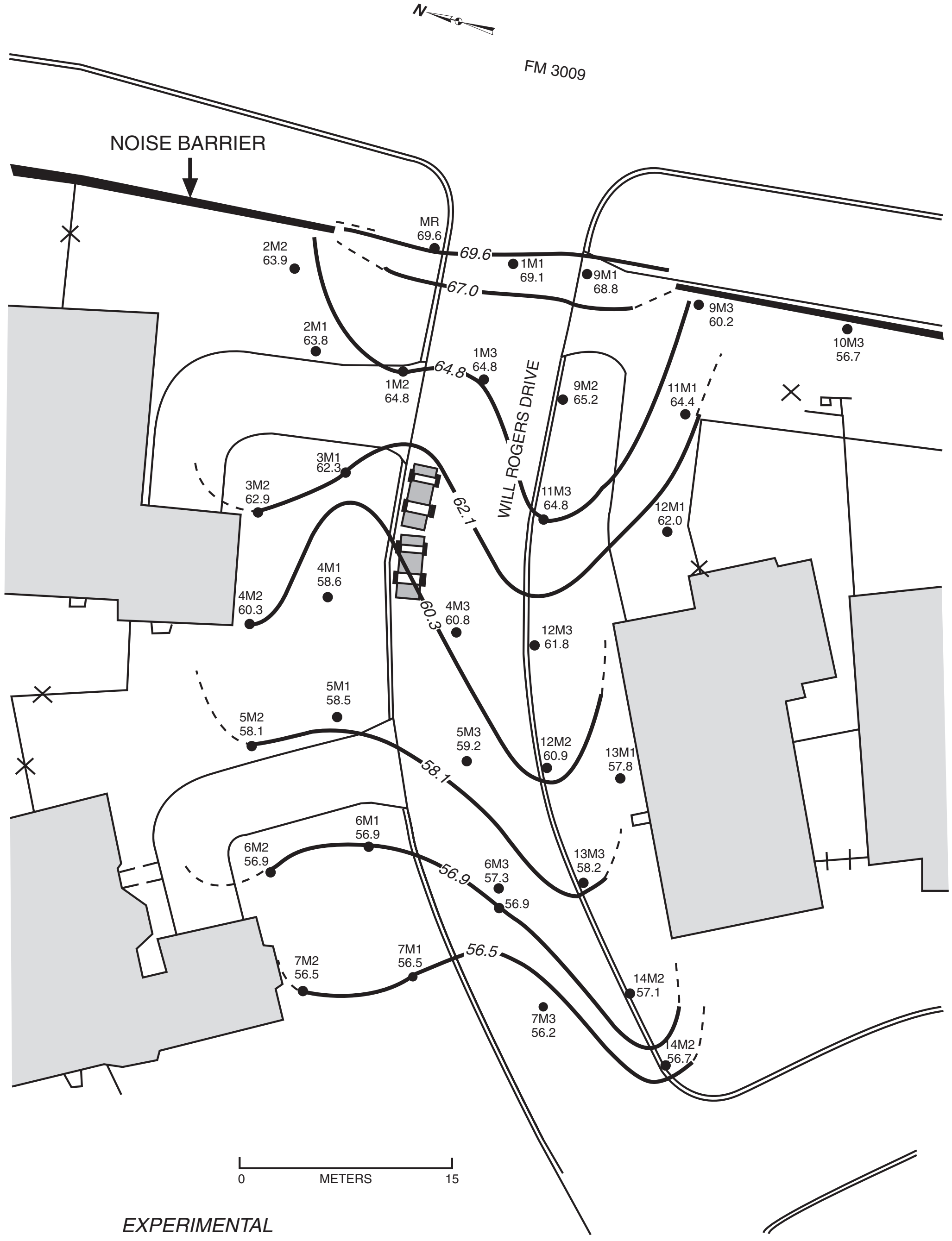


Figure 4.7 Constant noise level contours — Field measurements on Will Rogers Drive at FM 3009

The noise intrusion contour pattern derived using SoundPLAN modeling compares quite favorably with the measured noise level contours. The differences in the contour patterns in Figures 4.7 and 4.8 can be explained primarily by the fact that the SoundPLAN results are based on ideal site conditions that do not take into account specific trees and other vegetation, parked vehicles, fences, and other sound scattering obstacles. The predicted average noise levels occurring along the south curb of Will Rogers Drive agree very closely with the measured values, indicating that SoundPLAN is accurate when the site conditions are simple enough to be represented in the model (i.e., the straight brick masonry wall). Scattering and absorption of sound by the irregular geometries of the houses and lawns on the north side of the street, including the two parked vehicles, are apparently sufficient to cause the 1–2 dB differences shown in the two noise contour maps.

4.1.8 Cherrywood Street — Measurements and Results

Cherrywood Street enters the east half of Greenfield Village Subdivision from FM 3009 through a 16.5 m wide opening in the 4.6 m high noise barrier. This opening in the barrier is the smallest of the four street openings at the site. At this location, there is no parallel noise barrier located on the opposite side of FM 3009, only a moderately wooded area without houses. The elevation of Cherrywood Street slopes downward from that of FM 3009 at a downgrade of approximately 1.5%. Cherrywood Street is oriented at 90° relative to FM 3009 and is straight for 45 m into the residential area. Traffic flow conditions on FM 3009 during the measurements on Cherrywood Street averaged 1,165 autos/hour and 47 trucks/hour.

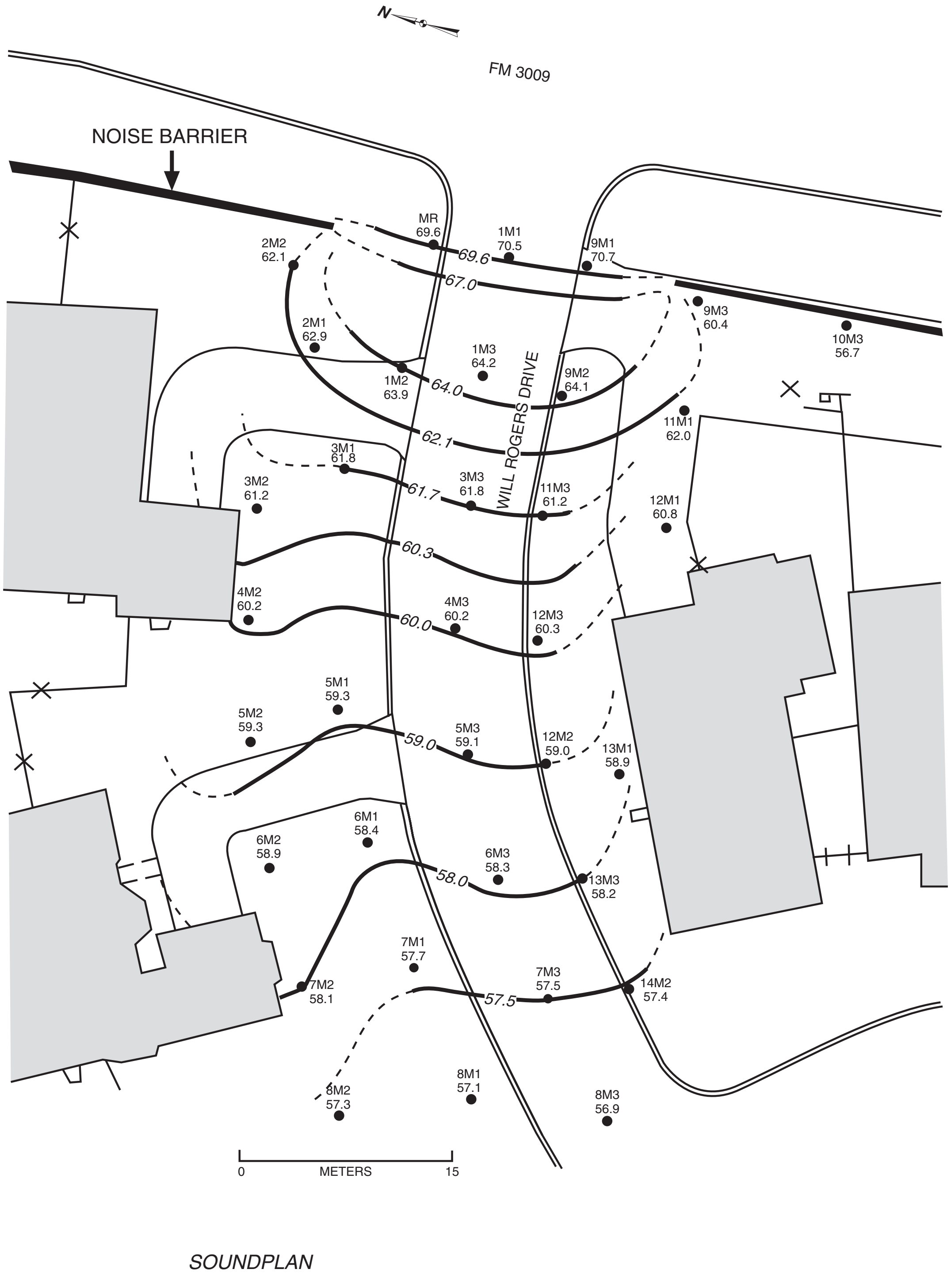


Figure 4.8 *Constant noise level contours — Computer model simulation for Will Rogers Drive at FM 3009*

Figure 4.9 shows several views of Cherrywood Street, illustrating the noise barrier opening and the residential area where the noise measurements were performed. The first 30 m of Cherrywood Street were free of any parked vehicles or other major sound scattering obstacles. This 30-m section of the street was of primary interest for the traffic noise measurements, given that the noise levels at greater distances from FM 3009 were more than 15 dB less than the noise level at the street entrance reference microphone.

(a) Noise barrier opening at entrance

(b) Street curvature (vehicle temporarily near microphones)

(c) Parked vehicles present during measurements

(d) Elevation change at residence at end of street

Figure 4.9 Cherrywood Street at FM 3009

Traffic noise levels were measured at thirty-four microphone stations, twenty-six of which were within the 30-m section of primary interest. The measured noise levels were adjusted to take into account their individual microphone calibrations measured during the data collection session and normalized to a common traffic load condition on FM 3009 using the average noise level readings at the reference microphone station. For the measurements on Cherrywood Street, the reference microphone was located at the left-hand curb of the street (when exiting to FM 3009) on the line joining the two noise barriers at the street opening.

Figure 4.10 shows the results of the traffic noise intrusion measurements on Cherrywood Street. The noise contours in this figure were interpolated using cylindrical wave spreading along the direction into the residential area and using linear interpolation in directions lateral to the street centerline. These noise level contours show that the traffic noise immediately behind the barrier is abated by 9 dBA (approximately the same as that on Will Rogers Drive). The contours also show that the noise level diminished relatively uniformly along the street in the absence of any sound-scattering obstacles. However, in comparison with the noise intrusion into Will Rogers Drive, the noise levels on Cherrywood Street decreased more rapidly with distance (approximately 4 dB greater reduction at 30 m on Cherrywood Street than on Will Rogers Drive). This greater degree of noise abatement is attributed primarily to the smaller street opening in the noise barrier at Cherrywood Street—an opening only 67% as wide as the opening on Will Rogers Drive. Noise levels below 56.1 dBA were not contoured because of interference from nontraffic background sounds in the residential area.

Figure 4.11 shows a corresponding traffic noise contour map for Cherrywood Street derived from the SoundPLAN computer model. The noise intrusion contours created by SoundPLAN compare very favorably with the experimental measurements, especially in their uniformity along the street and in the front yards of the houses. However, the actual noise levels predicted by SoundPLAN were about 3 dB higher than the field values at the 30-m distance position along the street. The reason for this difference is that the computer model did not take into account the downgrade slope on Cherrywood Street. Comparisons of the SoundPLAN predictions for noise intrusion at Cherrywood Street and Will Rogers Drive indicate that the noise contours within the first 20–25 m along the two streets are essentially the same, whereas the predicted noise on Cherrywood Street diminishes more rapidly beyond the 30-m distance. The main differences in these two computer simulation models are the widths of the noise barrier openings and the representations of the houses along each street.

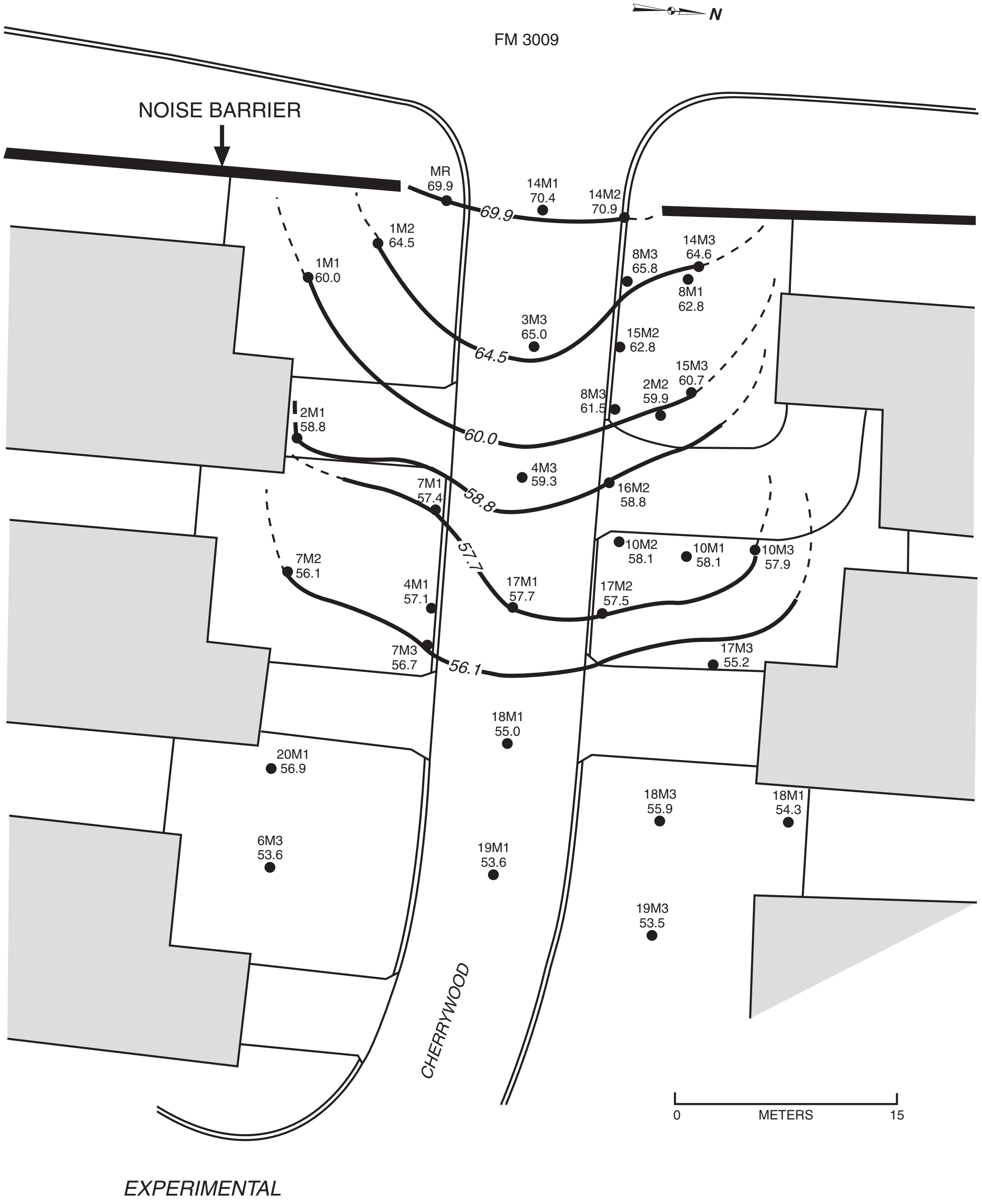


Figure 4.10 Constant noise level contour — Field measurements on Cherrywood Street at FM 3009

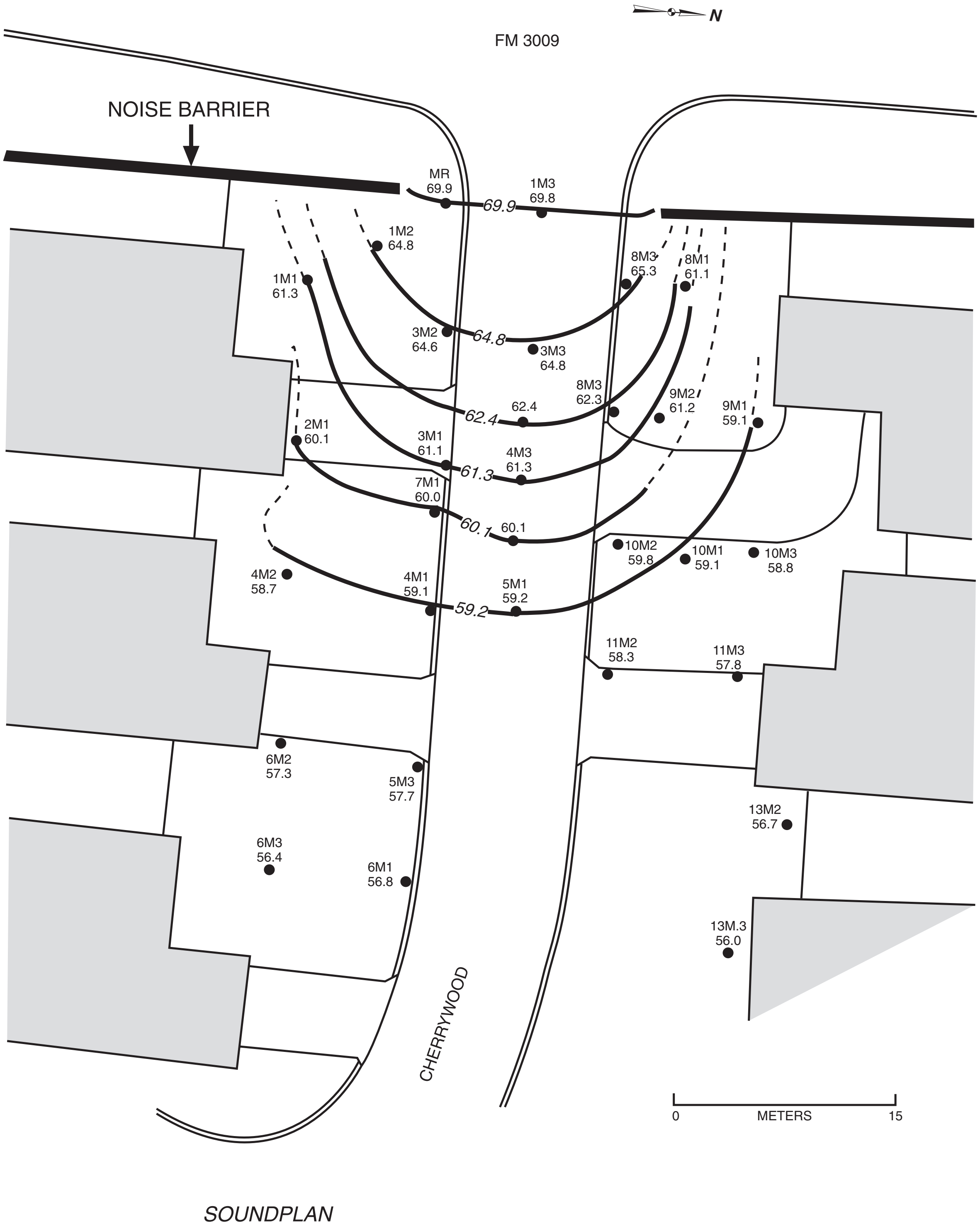


Figure 4.11 Constant noise level contours — Computer model simulation for Cherrywood Street at FM 3009

4.1.9 Cyrus McCormick Street — Measurements and Results

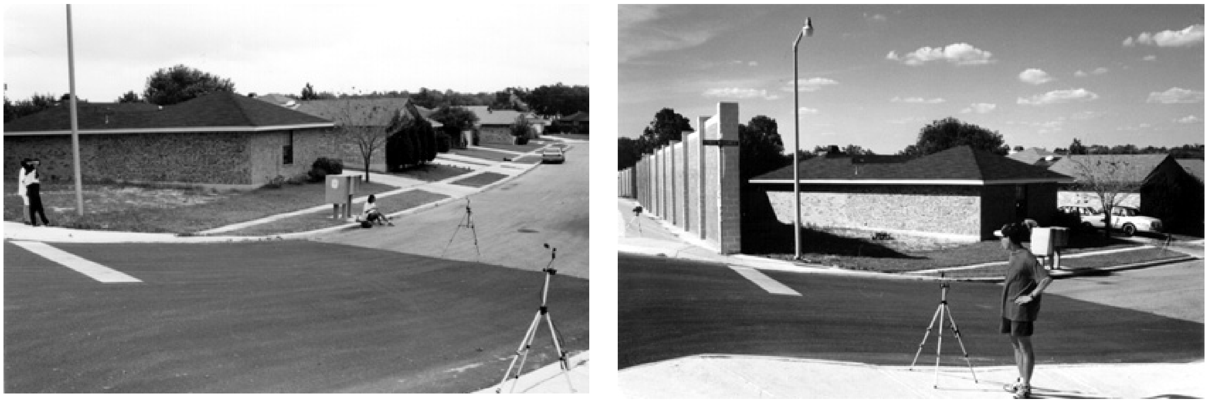
Cyrus McCormick Street enters the east half of Greenfield Village Subdivision from FM 3009 through a 21.3 m opening in the 4.6 m high noise barrier. A wooded area without houses is located on the opposite side of FM 3009. Cyrus McCormick Street curves quickly after entering the residential area and then continues along a straight path oriented at a 20° northeast angle. Five houses are on the south side and four houses are on the north side of the street, most of which have their foundations and front entrances at ground levels elevated 1–2 m above the street level. The centerline of Cyrus McCormick Street slopes at an estimated average downgrade of 12% until the street elevation is approximately 4 m below the surface elevation of FM 3009 (at a distance of approximately 27 m along the centerline of the street). Thus, Cyrus McCormick Street and its houses are substantially below the FM 3009 roadway; the street is also oriented at a 70° angle with respect to the FM 3009 roadway and noise barrier. Traffic flow on FM 3009 during the measurement sessions on Cyrus McCormick Street averaged 1,196 autos/hour and 34 trucks/hour.

Figure 4.12 shows several views of the traffic noise test area on Cyrus McCormick Street, illustrating the depressed elevation of the street and the somewhat higher elevations of the houses with respect to the street. The front yards of the houses facing Cyrus McCormick Street are generally smaller than those of houses on other streets in the subdivision. These smaller yards, when combined with the depressed elevation of the street, form a relatively distinct channel for guiding the traffic noise along the street. Cyrus McCormick Street was free of parked vehicles 50 m into the residential area. Several vehicles that were often parked in the driveways of the houses were moved or absent during the morning and afternoon noise measurement sessions. The first 30 m along the street were of primary interest in the traffic noise intrusion measurements.

Figure 4.13 shows the results of the traffic noise measurements on Cyrus McCormick Street. The noise contours in this figure were interpolated using cylindrical wave spreading along the centerline of the street and linear interpolation in directions lateral to the centerline. The contours indicate a much more rapid fall-off of the traffic noise level with distance along the street than those observed on the other streets. This rapid decrease is caused by the down-slope of the street. Guided confinement of the stronger noise levels along the angled direction of the street is also noticeable in the contours. Noise levels below 57.1 dBA were not contoured because of the interference caused by nontraffic background sounds in the residential area.

(a) Noise barrier opening at entrance (note elevation ref FM 3009)

(b) Higher residential elevations



(c) Reference microphone in foreground

(d) Primary receiver yard—North side

Figure 4.12 Cyrus McCormick Street at FM 3009

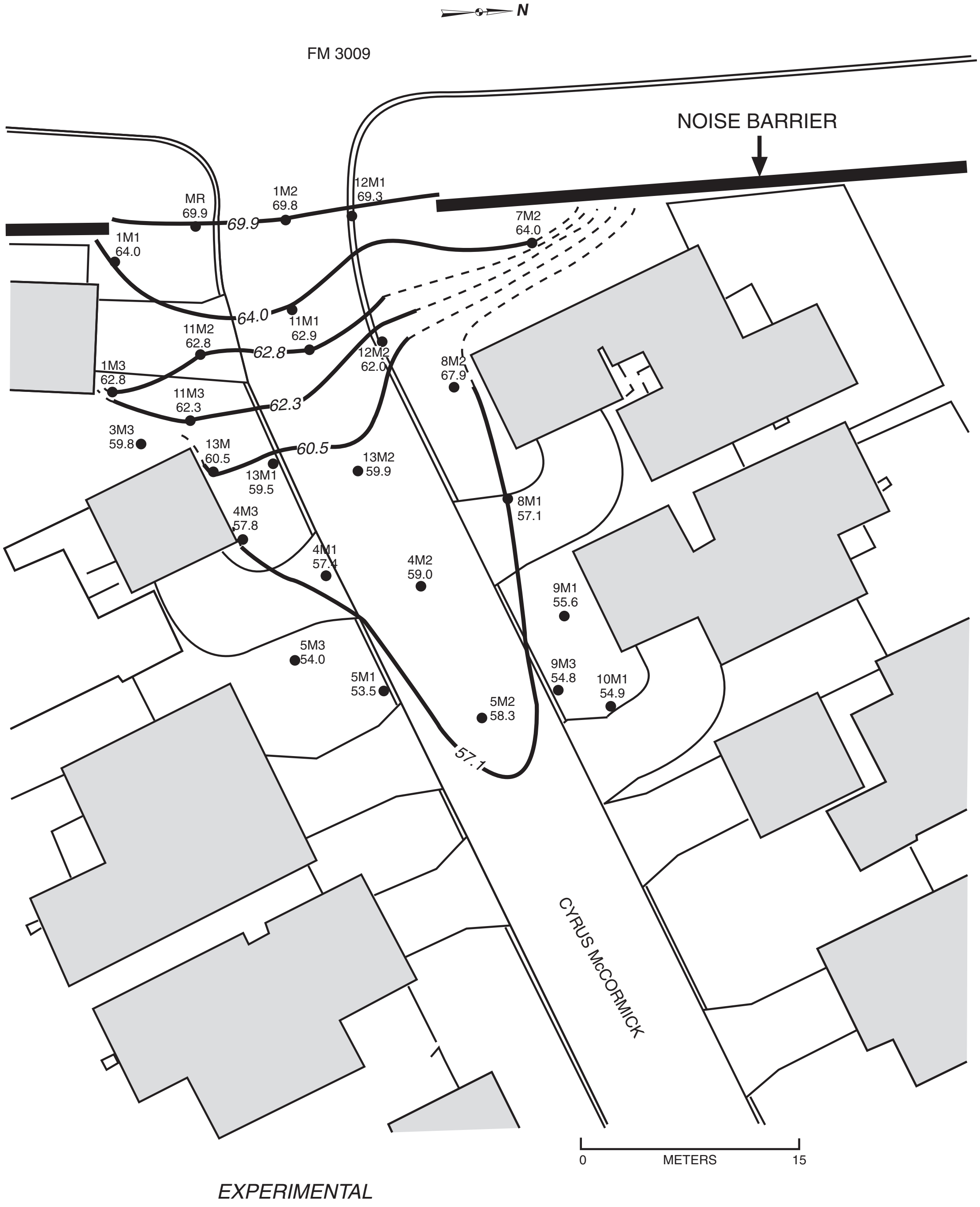


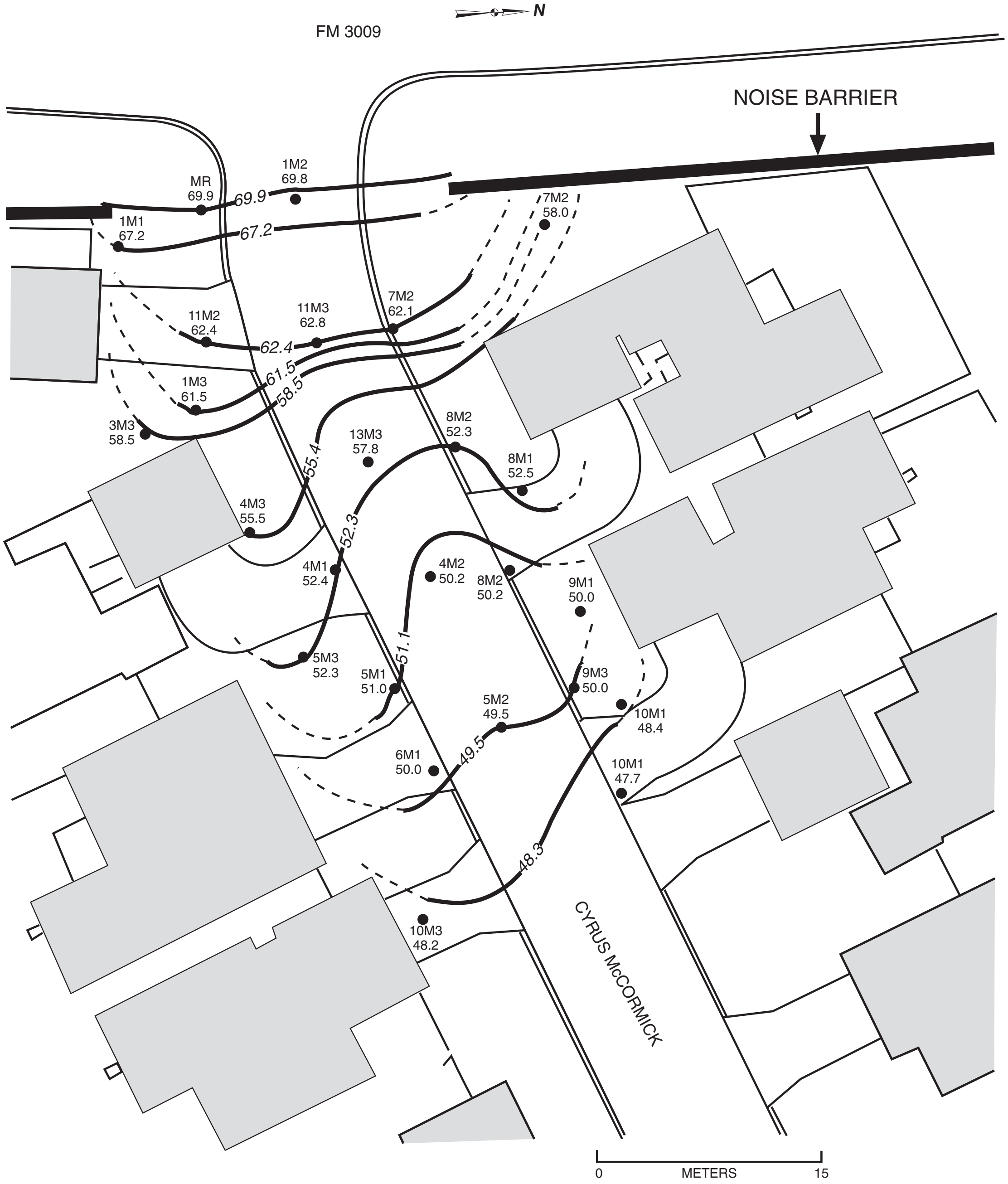
Figure 4.13 Constant noise level contours — Field measurements on Cyrus McCormick Street at FM 3009

Physical differences in the elevations of Cyrus McCormick Street relative to those on Will Rogers Drive and Cherrywood Street prevent detailed comparisons of their respective traffic noise intrusion distributions. Nevertheless, since the noise conditions at the primary receiver residences are of greatest concern, these sections of the noise contour maps can be compared, given that they are at approximately the same elevation as the FM 3009 roadway. When compared in these primary residence zones (typically within about 7–9 m beyond the noise barrier into the residential streets), the noise intrusions are approximately the same. At greater distances into the residential areas, Cherrywood Street and Cyrus McCormick Street exhibit measured noise intrusion levels lower than those on Will Rogers Drive.

Figure 4.14 presents a contour map of noise intrusion conditions on Cyrus McCormick Street predicted using the SoundPLAN simulation. In comparison with the measured noise contours, the predicted noise levels within 7–9 m of the barrier opening are in good agreement. At greater distances into the residential area, the predicted noise levels are considerably lower than the measured values. We believe this discrepancy is primarily a result of the sound-guiding effects of the houses (elevated above street level) not being modeled in the simulation. The estimated down-slope of Cyrus McCormick Street was represented in the model by lowering the microphone and the ground surface elevations to approximate the street elevation. However, the necessary details on the houses and their elevations above the street were not available for more exact modeling. As a consequence, the modeled sounds reflecting from the houses are significantly lower than those occurring at the actual site.

4.1.10 Utility Access Alley — Measurements and Results

The utility alley located between Will Rogers Drive and Patrick Henry Street on the west side of FM 3009 has a 4.6 m wide opening in the 3.7 m high noise barrier. This alley is lined along its 5.2 m wide easement by wooden fences that are 1.8 m high on both sides, creating a narrow sound-confining path into the residential area. The noise intrusion into this alley, although much less than that intruding into the residential street areas, potentially increases the traffic noise levels in the backyards of the primary receiver residences adjacent to the alley opening. The alley had an elevation approximately the same as that of the FM 3009 roadway, and had a moderately heavy grass ground cover at the time of the measurements. Noise levels were not measured in the backyards of the residences adjacent to the alley.



SOUNDPLAN

Figure 4.14 Constant noise level contours — Computer model simulation for Cyrus McCormick Street at FM 3009

The reduction in noise abatement at this utility alley opening was evaluated by applying source-referenced noise level measurements along its centerline. The resulting sound transmission loss data, extending approximately 32 m into the alley, are directly comparable with data obtained from measurements behind a continuous section of the barrier located parallel to Robert Derrick Street (see section 4.2).

Figure 4.15 shows two views of the utility alley. A 4.7 m high noise barrier is located opposite the alley on FM 3009. Figure 4.16 shows the experimentally measured sound transmission loss extending 32 m into the alley. Background noises not related to the traffic on FM 3009 prevented meaningful measurements at greater distances from the barrier opening. Also presented in Figure 4.16 are sound levels scaled from source-referenced traffic noise measurements at a continuous section of the same noise barrier (described in detail in section 4.2) and predicted sound levels derived using the SoundPLAN computer model.

Traffic noise intrusion into the alley is noted to be approximately 2.1 dBA above the experimental noise level measured at a distance of 9.1 m behind a continuous section of the same noise barrier. A significant part of this noise abatement reduction in the alley is regained in the backyards of the primary receiver residences because of the wooden fences lining the alley. The sound transmission loss along the centerline of the alley, as predicted by the SoundPLAN model, is within 1–2 dB of the measured values. In this simulation, the wooden fences were simulated as reflecting walls that are 1.8 m in height. Also shown in Figure 4.16 are predicted values of traffic noise at positions in the backyards of two of the residences. At a location 9.1 m behind the noise barrier and 6.1 m from the wooden fence, this predicted noise level is 58.8 dBA — a value only 2.3 dB greater than that typically achieved behind a continuous noise barrier.

4.2. NOISE BARRIER EFFECTIVENESS

4.2.1 Measurements in Primary Receiver Area

An important consideration in evaluating the noise abatement effectiveness of the noise barrier on FM 3009 is to experimentally verify the degree of noise reduction at one or more primary receiver residences located behind the continuous barrier panel. Several primary receiver residences are located behind the longer sections of the barriers on both sides of FM

3009. However, most of these houses have yard privacy fences and are oriented and spaced relative to each other in such a way as to block a reasonably straight “walk-way” measurement line behind the barrier.

(a) Noise barrier opening at entrance of alley

(b) Microphone stations in alley

Figure 4.15 Utility access alley at FM 3009 (north of Will Rogers Drive, looking west)

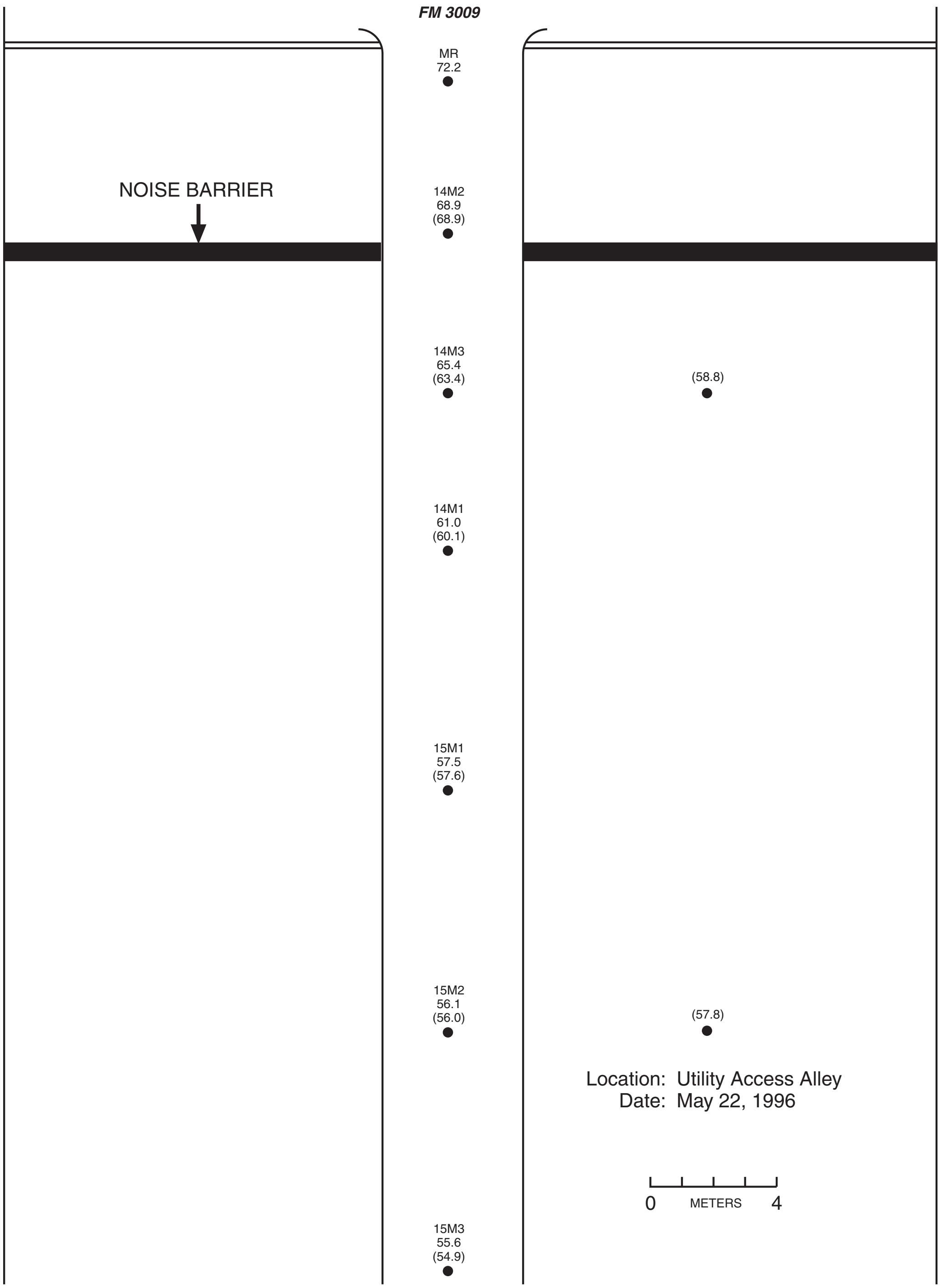


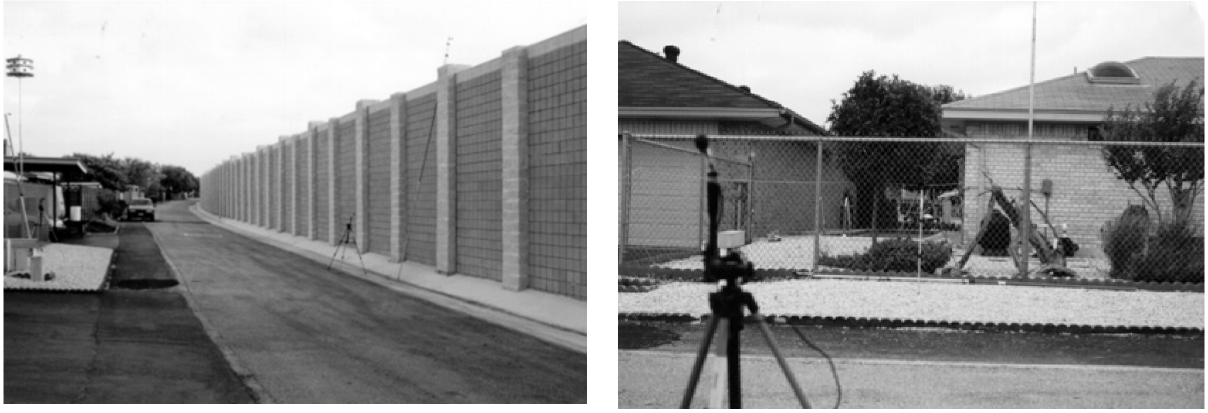
Figure 4.16 Microphone station layout and noise level data for utility access alley at FM 3009. All sound levels are in dBA. Measured sound level values are unbracketed. Computer-simulated levels are in parentheses.

The most favorable setting for this type of measurement was found to be between two houses located in the midsection of Robert Derrick Street on the west side of FM 3009. The height of the noise barrier at this location was approximately 4 m above the roadway surface and the primary receiver property behind the barrier was at an elevation 4.4 m below the top of the barrier. The primary receiver houses at this location, although spaced only 10 m apart, had an unobstructed measurement line between them and were surrounded by an open-wire (chain-link) fence.

Another consideration for selecting this location for the noise barrier effectiveness test was that an open field (no noise barrier) was directly opposite the Robert Derrick Street test area on the west side of FM 3009. Thus, by conducting referenced sound level measurements behind the noise barrier and in the open field, a good technical evaluation of the noise barrier performance could be obtained.

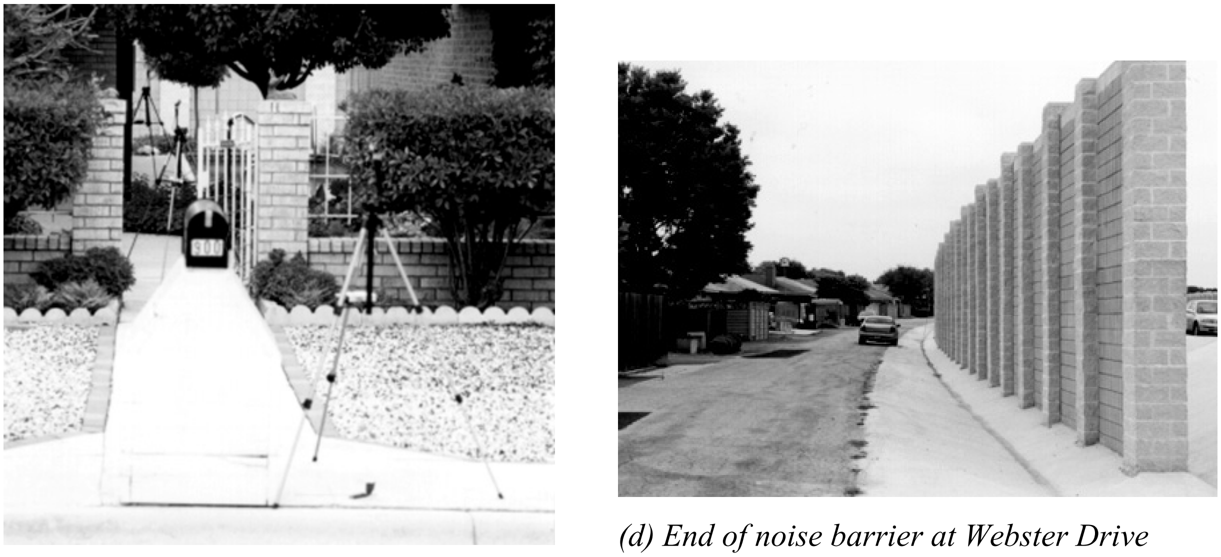
Figure 4.17(a) shows the layout of the houses and the microphone stations used in the barrier effectiveness measurements. The reference microphone was located approximately 0.6 m directly above the top of the barrier; seven microphone stations were recorded behind the barrier. All microphones were set up at a height of about 1.2 m except one, which was located in the back yard area at a height of about 3 m (this station was used to measure the influence of receiver height). At a common position (about 10 m behind the barrier) the noise level at the 1.2 m microphone height was 61.1 dBA and, at the 3 m microphone height, 66.9 dBA—a difference of 5.8 dB. This difference indicates the importance of the receiver height in characterizing the noise abatement.

Figures 4.17(b)–4.17(d) show photographs of the microphone station setups and the residential test environment behind the noise barrier and between the two houses selected for the tests. The relatively close spacing of the houses and the presence of shrubbery are evident in these photographs. Figure 4.18 presents a plan view of the measurement site behind the continuous barrier. This sketch shows the microphone positions relative to the barrier and the structural outlines of the two houses.



(a) Garage access alley behind noise barrier

(b) Traffic noise measurements between houses (toward Robert Derrick Street)



(c) Noise measurement path viewed from Robert Derrick Street

(d) End of noise barrier at Webster Drive

Figure 4.17 Behind continuous noise barrier at Robert Derrick Street

4.2.2 Measurements in Adjacent Open Field

The noise measurement setup used in the open field is illustrated in Figure 4.19. The reference microphone station used for these measurements was the same location (0.6 m above the top of the east side noise barrier) as that used for measurements behind the barrier. Six microphone stations were set up at 1.2 m heights to measure and record the traffic noise to a distance of approximately 60 m away from the centerline of FM 3009. Accurate determination of traffic flow conditions was derived from videotape recordings obtained during each of the measurement sessions.

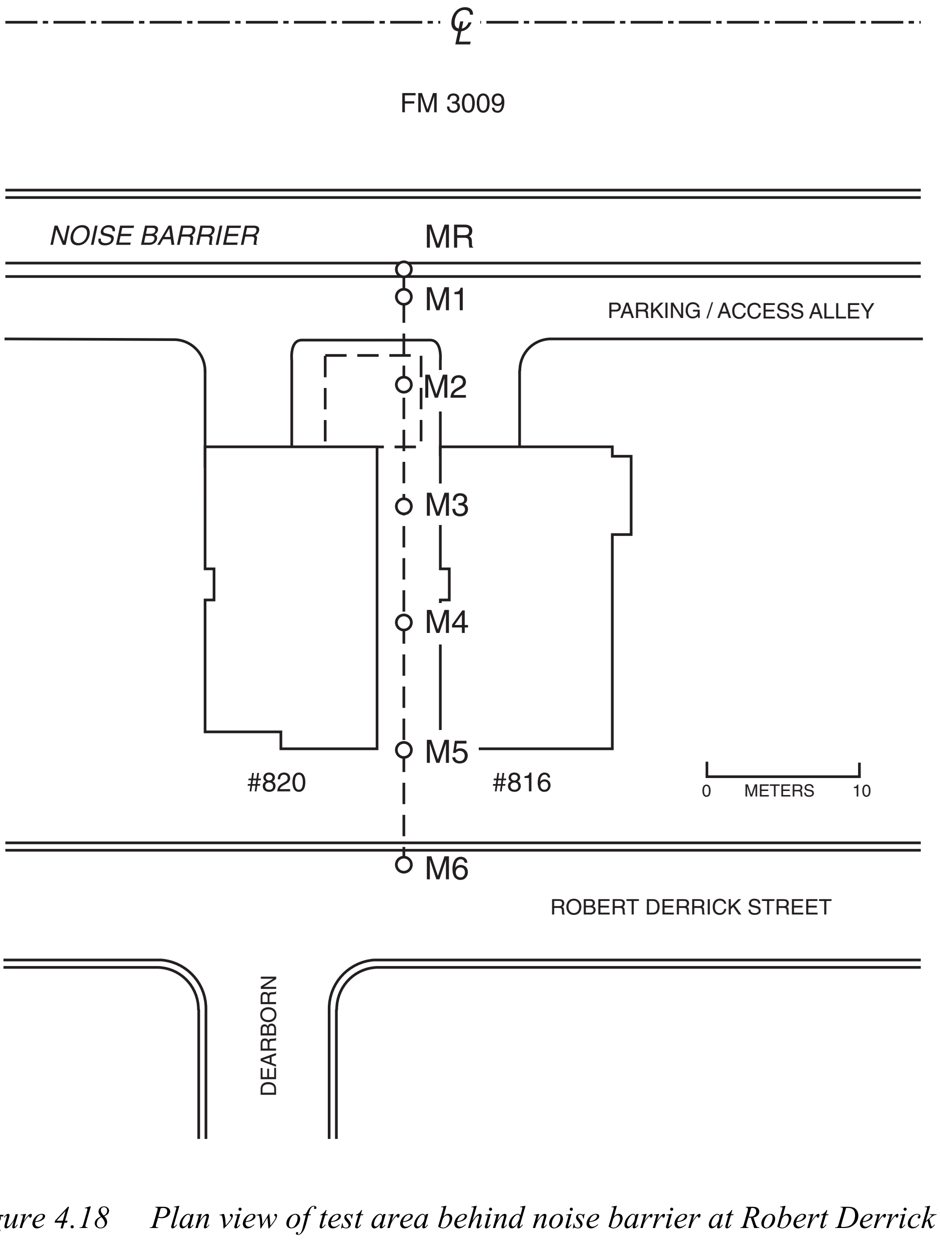
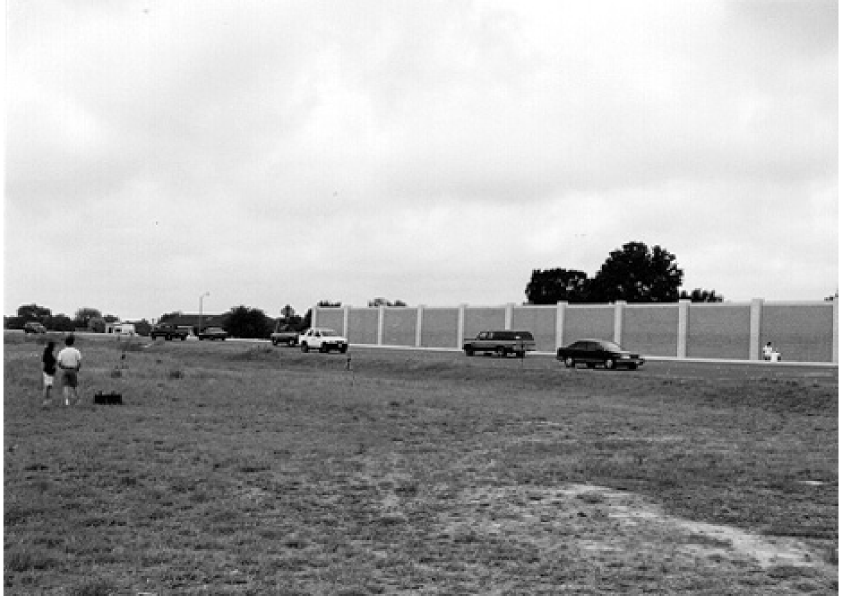


Figure 4.18 Plan view of test area behind noise barrier at Robert Derrick Street

(a) Reference microphone station at top of noise barrier



(b) Noise barrier at Robert Derrick (back side of barrier is shown in Figure 4.17)

Figure 4.19 Traffic noise measurements in open field on FM 3009 opposite from barrier on Robert Derrick Street

4.2.3. Continuous Noise Barrier Test Results

Figure 4.20 shows a quantitatively referenced comparison of the traffic noise measured behind the barrier with that measured in the open field. This comparison shows that the noise barrier is very effective in reducing the noise from FM 3009, especially in the area close to the barrier. As shown in Figure 4.20, there is more than 10 dB noise reduction immediately behind the barrier. In the distance range between 10 m to 37 m, extending into the front yards of the houses, the barrier effectively reduces the noise by about 5 dB.

Figure 4.21 compares the measured noise levels with those derived from the SoundPLAN computer model. This comparison shows that the predicted noise levels are quite close to the measured values. In the SoundPLAN simulation, the microphone stations were at the same height as those used in the behind-wall measurements. However, because the FM 3009 roadway was elevated about 1.2 m above the level of the open field, and because the field had a substantial grass cover, the measured noise levels are lower than those predicted by the computer simulation.

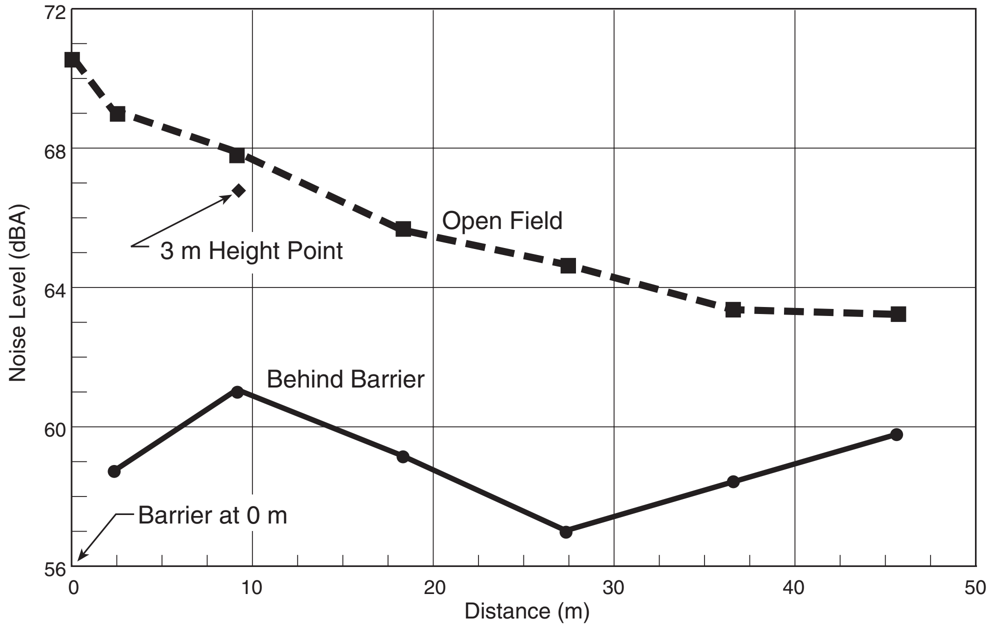


Figure 4.20 Noise barrier effectiveness for primary receivers located on Robert Derrick Street

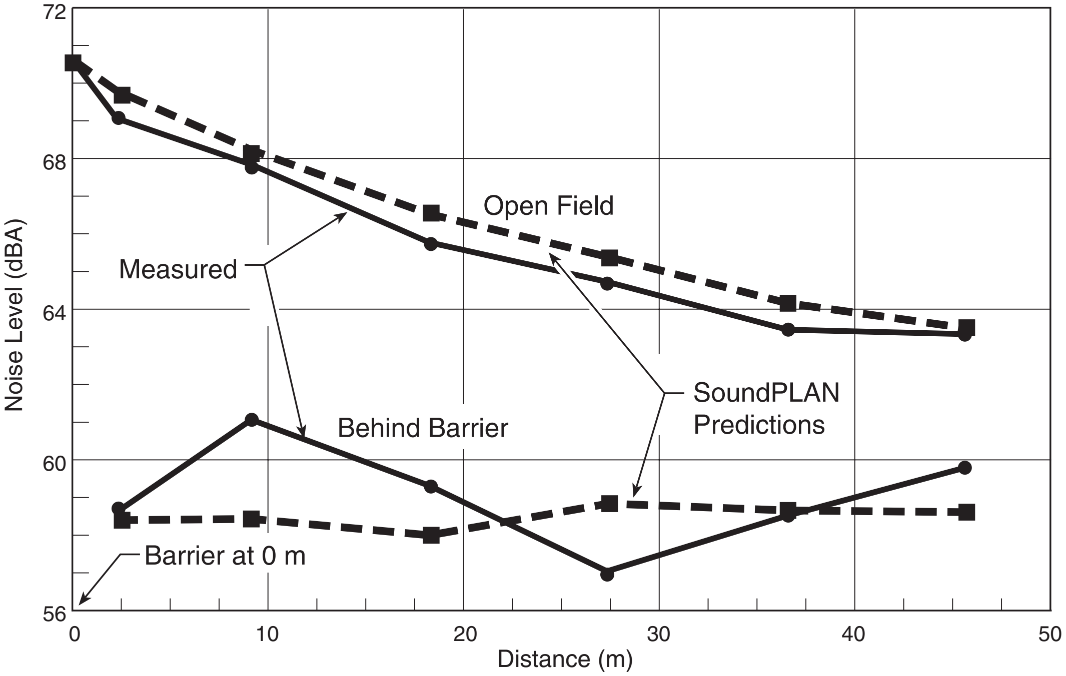


Figure 4.21 Comparison of field measurements and SoundPLAN predictions

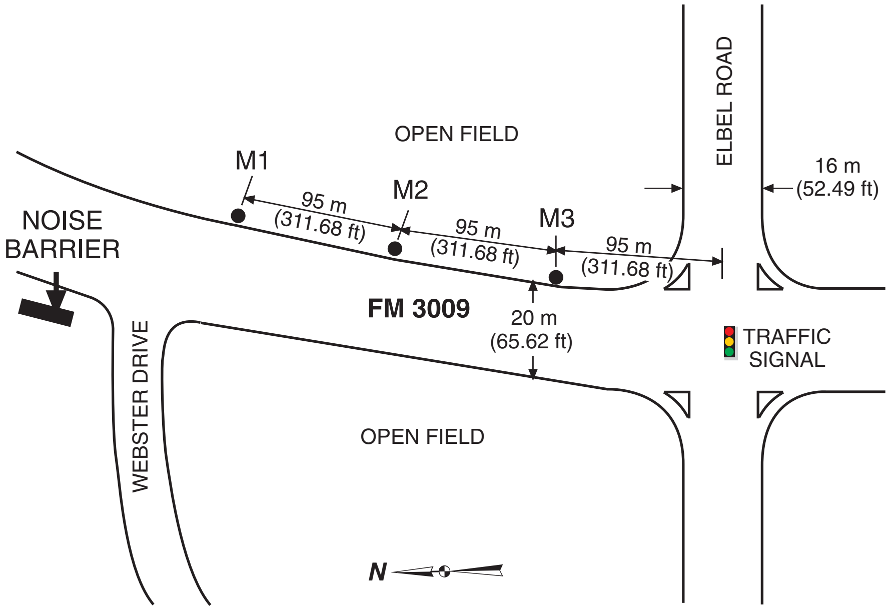
4.3 HEAVY TRUCK ACCELERATION NOISE

Description and Goals of the Test: Much of the traffic noise intruding into the Greenfield Village Subdivision is caused by the engine power changes and the acceleration of heavy trucks traveling on FM 3009. In analyzing this form of traffic noise, we recorded noise emissions generated by heavy trucks starting from a stopped position at the Elbel Road–FM 3009 traffic signal and accelerating to steady roadway speed traveling northward on FM 3009. The elevation grade on this section of FM 3009 is approximately +1.5% and the traffic speed limit is 45 mph. While the drivers of the trucks did not participate in these tests (in order to provide details on such operating parameters as engine speed, gear changes, and ground speed), the tests were regarded as successful in supporting the development of an analytical model of the noise.

The field setup employed in the tests is illustrated in Figures 4.22(a) and (b), which show the FM 3009 roadway layout and the field setup, respectively. The goal of the test was to obtain time-dependent noise observations at three microphone stations located along the vehicle travel path and, from video evidence of the vehicle operation, devise a predictive model of the vehicle drive-by noise level at each microphone station. For this purpose, only those instances in which an individual truck was observed with only a few other relatively low-noise vehicles present could be used in the study. One event of this type was recorded and studied in detail.

Field Measurements: Four microphone stations were used to record curbside traffic noise at the locations shown in Figure 4.22(a). One microphone station, placed at the traffic signal, was intended to record the engine noise generated as the truck begins to move. However, for the truck vehicle event selected for evaluation, this initial noise level was not usefully representative of the engine power and noise level of the truck. Consequently, only three of the microphone stations were useful in the acceleration noise test. Microphone stations M3, M2, and M1 were located at 95 m, 190 m, and 285 m, respectively, from the traffic signal. Along the vehicle travel path, FM 3009 has a gentle curvature to the east (radius of curvature approximately 1,500 m). Each sound level meter unit was placed within 1 m of the roadside curb at the immediate right-hand boundary of the far right traffic lane. The truck being observed first traveled in the far right lane until passing station M3, changed to the inner right lane until passing station M2, and finally returned to the far right lane before passing station M1.

The sound level meters were programmed to record a 20-minute time interval of traffic drive-by events, during which time twelve to fifteen heavy trucks were expected to travel in the northbound direction from the traffic signal. The traffic noise sound levels were sampled 16 times/second using an A-weighted frequency response; each sequence of thirty-two samples was then averaged to form a relatively smooth time series record of the transient vehicle noise. Large trucks typically exhibited a noise level in the range of 90–95 dBA at the closest point of approach to the microphone (approximately 3–5 m lateral distance). All vehicles stopping at the traffic signal were noted to accelerate from the green light to a final speed of 45-50 mph within a distance 90–120 m.



(a) Microphone station layout

(b) Field set up

Figure 4.22 Field location and microphone stations for truck acceleration noise test

The truck event selected for evaluation was an eighteen-wheel chemical tanker truck that traveled the three-microphone monitor path with essentially no noise interference from other vehicles (a total travel time interval of about 35 seconds). The video record of this truck, taken from a location opposite microphone station M1, indicated when the traffic signal turned green, showed variations in diesel smoke from the engine exhaust stack corresponding to gear shifting or engine power variations, and showed the position of the truck when it changed traffic lanes. Identification of the 35-second sound level time-series sequence associated with this vehicle in the 20-minute data record was facilitated by time synchronization between the sound level meter record and the time stamp displayed on the videotape.

Mathematical Model: A moving, noisy vehicle may be represented in a simple analytical model as a point sound source traveling in a stationary homogeneous atmosphere along a specified path. A basic scenario for such a model is one in which the vehicle starts from a stationary position, as at a traffic signal intersection, and undergoes constant acceleration along a straight path until it reaches a final roadway speed. For a sound level meter located near curbside and about 100 m beyond the traffic signal, the vehicle first generates a low-level sound that increases as the distance between the vehicle and the microphone station closes. During this time, the amplitude of sound from the approaching acoustic point source decreases inversely with the closing distance to the microphone. When the vehicle reaches the closest point of approach to the microphone, the sound amplitude is at the maximum value. Beyond the closest point of approach, the sound amplitude then decreases as the vehicle recedes from the microphone. An analytical formulation of this model is presented in Appendix B.

In the presence of background noise, the time-dependent sound amplitude from the moving vehicle may be expressed as:

$$A(t) = 20 \log_{10} \left[10^{\frac{BL}{20}} + 10^{\frac{SL}{20}} R^{-1}(t) \right] \tag{4.1}$$

where

BL = background noise level (dBA),

SL = reference source level of the vehicle represented as a point source (dBA at 1m), and

$R(t)$ = time-dependent slant distance between the moving vehicle and the microphone station.

The general form of the slant distance, $R(t)$, is:

$$R(t) = \sqrt{d^2 + D^2(t)} \qquad (4.2)$$

where

d = curbside offset distance of the microphone from the vehicle path at the closest point of approach, and

$D(t)$ = time-dependent closing distance between the vehicle and the closest point of approach to the microphone.

Expressed in terms of the vehicle acceleration and the time at which it is at the closest point of approach, the closing distance is:

$$D\,(t) = a_0 t_m \left(t_{cpa} - t\right) - \frac{a_0}{2}\left(t_{cpa} - t\right)^2 \qquad (4.3)$$

where

t_{cpa} = time at which the vehicle is at the closest point of approach (maximum sound level), and

t_m = time required for vehicle to accelerate from stationary start to final roadway speed.

The Metrosonics dB 3100 sound level meters used in the field tests were programmed to record sixteen sound amplitude readings per second and to calculate and store sequential averages of thirty-two readings each, corresponding to a time-series of 2-second average values of the vehicle transient noise signal as it approaches and passes the microphone. In order for the analytical model calculations to be comparable with the experimental data, this signal averaging process was also applied in the mathematical model by modifying Equation (4.1) to the discrete time form:

$$A\left(t_k\right) = 20\log_{10}\left[10^{\frac{BL}{20}} + \frac{10^{\frac{SL}{20}}}{N+1}\sum_{n=0}^{N} R^{-1}\left(t_k + n\Delta t\right)\right] \tag{4.4}$$

where

Δt = 1/16 sec = sound amplitude sampling interval,

n = *0,1,2,...,*N; number of sound amplitude samples in each updated average value (N+1 = 32), and

k = 0,1,2...,K; number of 2-second updates in the time series representing the vehicle transient noise signal.

This mathematical model was implemented on a standard spreadsheet using the formulas in Appendix B to calculate the transient vehicle noise levels observed at three microphone stations spaced at successive 95-m distances from the traffic signal.

Comparison of Analytical Model with Field Measurements: One isolated pass of a heavy truck was recorded by the three sound level meters during a 20-minute observation interval. It was the first vehicle in line at the traffic signal and, therefore, could be timed in its video record from the time the traffic signal changed to the time at which it was at the closest approach to the first microphone station. This travel time to the first microphone was sufficient, when combined with the records obtained from the sound level meters, to completely define the mathematical model. Knowing the curbside offset distances, d, at each microphone station, the apparent vehicle acceleration, a_o, and its equivalent point source reference sound level were adjusted by trial and error to fit the transient sound signal observed at the first microphone station. The time, t_m, at which the vehicle reached its final speed was also determined by trial and error by comparing the mathematical model response with the experimental measurements. For this first leg of the truck pass-by at the closest microphone station, the best-fit vehicle acceleration was found to be $a_0 = 1.31$ m/s, the equivalent reference source level was $SL = 114.3$ dBA at 1 m for a curbside offset distance of 3 m, and the best-fit time at which the vehicle reached its final roadway speed (21 m/s = 47 mph) was 16 seconds after starting from $t = 0$ at the traffic signal. Table 4.2 summarizes the parameters used in the analytical model to obtain the approximate best fit between the model responses and the three experimentally measured vehicle noise events.

Table 4.2 Analytical model parameters for approximate best fit to measured truck acceleration noise

MICROPHONE STATION	MIC. DISTANCE FROM TRAFFIC SIGNAL (m)	TIME OF MAX. NOISE LEVEL (sec)	CURBSIDE OFFSET DIST. (m)	EQUIVALENT POINT SOURCE REF. LEVEL (dBA at 1 m)
M3	95	12	3	114.3
M2	190	19.7	8	111.5
M1	285	26.3	3	111.5

Figure 4.22 shows the experimentally measured vehicle noise time functions observed at each microphone (broken lines) and the best-fit noise level responses calculated using the analytical model. Within the limitations of the field measurements, where a few lower-noise vehicles were also present during parts of the truck pass-by interval and the actual acceleration characteristics of the vehicle were unknown, the simulated noise levels and measured noise levels are in quite reasonable agreement. In particular, the model provides a very good simulation of the highest amplitude noise levels (in the range of 75–90 dBA), corresponding to the most annoying noise emissions generated by heavy trucks. Thus, for future studies of heavy truck acceleration noise, the results of this preliminary test will provide a basis for characterizing the noise disturbances caused by single truck vehicles operating at accelerating speed. Both the field measurements and the analytical modeling could benefit by incorporating vehicle speed measurements using a portable traffic radar unit and a limited series of field tests to characterize truck noise reference source levels when operating on different highway grades at different speeds.

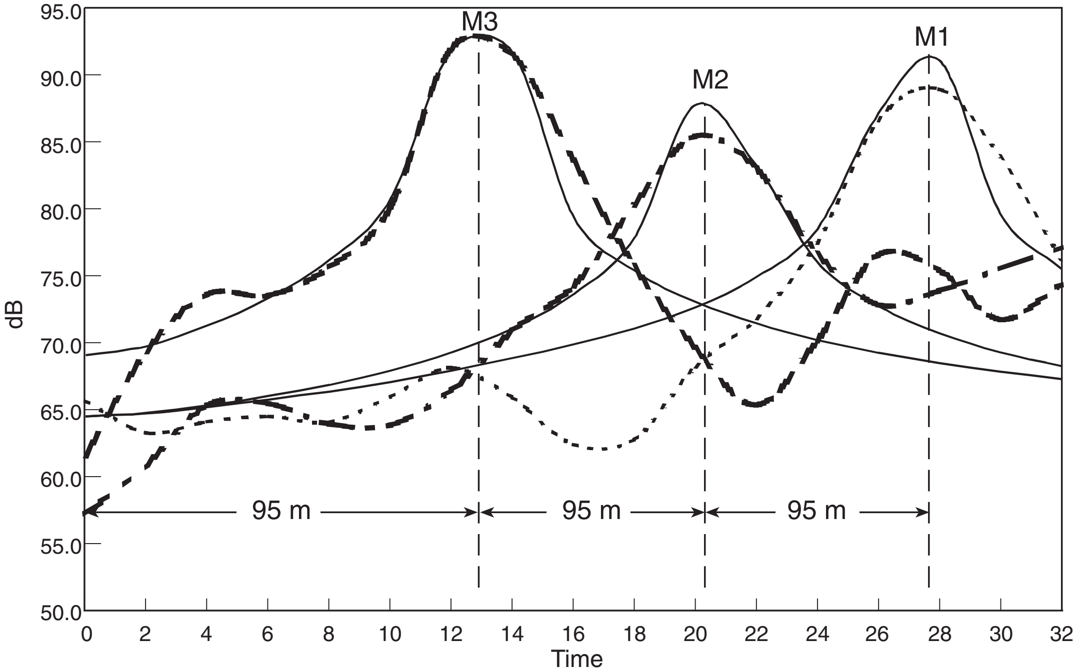


Figure 4.23 *Comparison of measured truck acceleration noise and analytical model simulation. Experimental data are shown by dashed lines.*

CHAPTER 5. DISCUSSION OF RESULTS

5.1 COMMUNITY TRAFFIC NOISE OPINION SURVEY

The opinion survey of residents in the Greenfield Village Subdivision provided a useful and informative assessment of the traffic noise occurring on FM 3009. The responses received from 130 residences in the area represented an exceptional overall survey response rate of 67%. The response rate from the thirty-two primary receiver residents was even higher at 78%.

Given that the noise generated by large trucks on FM 3009 was the problem that prompted the construction of the noise barriers, it was interesting to note that 62 percent of all respondents and 69 percent of the primary receiver respondents indicated that the barrier reduced the truck noise. The positive significance of this result is evident in Figure 3.1, which shows an obvious correlation of the affirmative survey responses with the locations of the respondents nearest FM 3009. Moreover, the positive responses provided by primary receivers in reply to other survey questions indicated that they are strongly aware of the FM 3009 traffic load and appreciate the beneficial effects of the noise barrier. The percentage of favorable secondary receiver responses to the survey questions was lower than that of the primary responses. This result suggests that the “no” secondary receiver answers imply that those residents are less aware of FM 3009 traffic noise as a problem.

The research team worked at five different residential sites during the field measurements. On these occasions, discussions with several primary residents and their neighbors regarding the traffic noise on FM 3009 clearly confirmed the results of the opinion survey.

5.2 NOISE INTRUDING THROUGH STREET OPENINGS

Systematic field measurements undertaken at three of the residential street openings into the subdivision provided a quantitative measure of the reduced effectiveness of the noise barriers. Additional field measurements of the insertion loss of a continuous section of the noise barrier and measurements in an open field without the barrier provided reference conditions by which the degree of noise intrusion at the street openings could be determined. The essential results of these measurements showed that quantitative measurements and analysis were capable of depicting the experimental distribution of traffic noise levels in the residential yards and showed the general influences of site conditions (e.g., parked vehicles, terrain variations, etc.) on the spatial distribution of the noise. The measurements on Will Rogers Drive were the most complete and descriptive of the potential irregularities in the noise distribution patterns caused by sound obstacles and other local site conditions. And because this street location also represented the widest opening in the FM 3009 noise barrier, it therefore characterizes the worst-case noise intrusion problem in the residential subdivision.

Traffic noise intruding through the street openings is significant in the immediate street entrance areas at the primary receiver locations. For example, at locations in the front yards of the primary receiver residences (approximate setback distance of 12–15 m from the centerline of Will Rogers Drive), the noise levels are reduced by 6 dB at a distance of 2.5 m behind the barrier, whereas the noise level at 2.5 m behind the continuous barrier is reduced by 12 dB. At the same setback distance but at the midpoint of the primary residence property frontage on Will Rogers Drive (approximately 20 m inside the street opening), the noise levels in the yards are reduced by approximately 2.5 dB, as compared with a reduction of 7 dB measured behind the continuous barrier. The same relative differences in noise levels were also found at the primary residences on Cherrywood Street and Cyrus McCormick Street, though the absolute noise levels on these two streets were about 2 dB lower than those on Will Rogers Drive.

The differing noise barrier opening dimensions, street curvatures, and house structures on the three entrance streets make detailed comparisons of noise intrusion difficult. However, a reasonable comparison is shown in Figure 5.1, which illustrates the measured sound transmission losses for the six test site locations on FM 3009. The noise levels for Robert Derrick Street (continuous barrier), open field (no barrier), and the utility access alley are interpolated directly from the field data. The noise levels shown for the three residential entry streets are interpolated from the noise level distribution contour maps for setback distances of 12–15 m from the centerlines of the streets. In addition to indicating the variabilities associated with the different test sites, these curves also show realistic noise intrusion trends occurring among the four openings in the noise barriers. In particular, the noise reduction effectiveness at the street openings is generally 4-6 dB less than that of the continuous barrier at the locations of the primary residences and their immediate neighbors. The utility access alley opening, at a width of only 15–25% of the street openings, has only 2–3 dB less noise reduction than the continuous barrier.

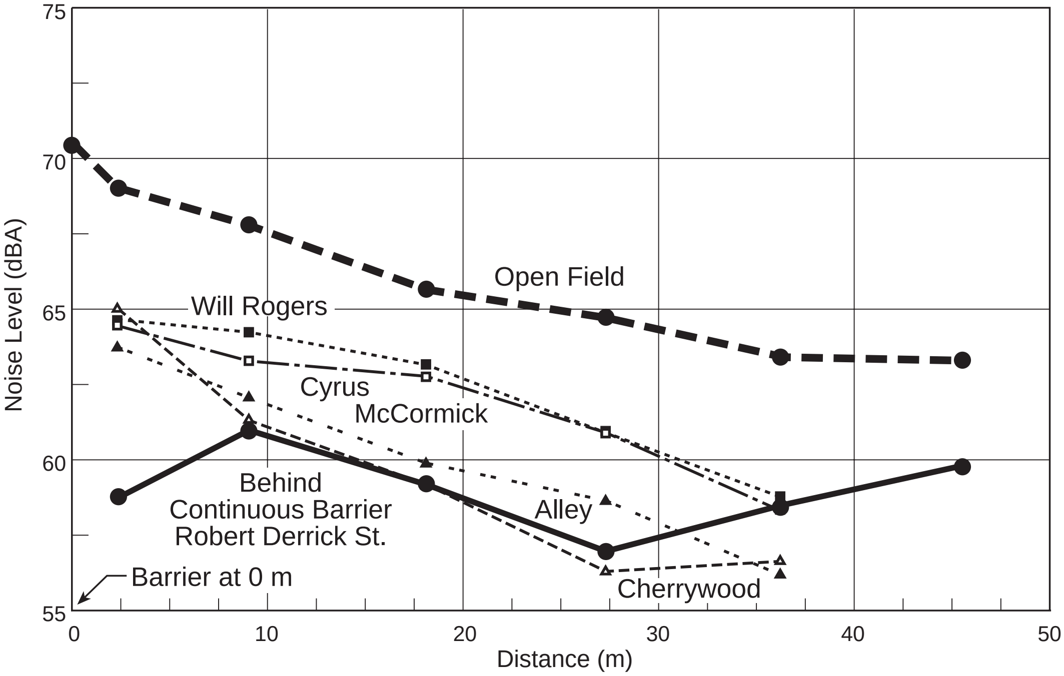


Figure 5.1 Traffic noise reduction measured at six locations along FM 3009

The effects of an opening in the noise barrier are dependent on the specific location of the primary receiver observation point with respect to the end of the adjacent barrier panel that provides its principal noise abatement. That is, the noise barrier panel located on the same side of the entrance street as the primary receiver residence provides the dominant reduction in traffic noise for that receiver. The noise barrier panel on the opposite side of the entrance street has only a secondary influence on the practical noise level observed in the primary receiver yard. For the specific conditions on FM 3009, the noise barrier panels on the opposite side of the street openings provide negligible noise reduction (less than 1 dB) for openings greater than approximately 9.5 m—an opening width slightly smaller than the actual curb-to-curb widths of the residential streets. This is illustrated in Figure 5.2, where computer simulation calculations were used to characterize street openings ranging from 0 m (continuous barrier) to the actual street openings for six different primary receiver locations in the streets where field measurements were recorded. The differences in these noise levels are governed primarily by the specific front yard positions at which the receiver is located with respect to the end of the adjacent noise barrier. The south side of Cyrus McCormick Street represented the worst-case condition among all of the street openings tested, a result primarily of the small size of the primary receiver front yard and of the limited effectiveness of the adjacent noise barrier in providing noise shielding. Thus, in assessing the degrading effects of street openings in a noise barrier, emphasis must be placed on the barrier location relative to the primary receiver residence position rather than on the width of the street opening, though minimizing the opening width is generally always beneficial.

5.3 NOISE BARRIER EFFECTIVENESS

The continuous noise barriers located on FM 3009 are presently effective in meeting the FHWA and TxDOT traffic noise abatement requirements for residential areas. The 1996 traffic load occurring on FM 3009 is greatest during the morning and evening rush hours, with typically 1,100 vehicles/hour (including up to 88 heavy trucks/hour). As traffic density on FM 3009 increases in the future, there will be a concomitant increase in traffic noise in the adjacent residential areas. Although the insertion loss provided by the noise barriers will not change, the subjective effectiveness of the barriers with respect to the 1996 traffic noise as reference will be reduced as the highway traffic increases. This decline in effectiveness will be noticed first at the primary receiver residences located at the residential street openings. Figures 5.3 and 5.4 help clarify the traffic noise growth versus traffic density at the street openings onto Will Rogers Drive and onto Cyrus McCormick Street. Figure 5.3 shows how sequential doublings of the traffic density on FM 3009, beginning with the present-day 1996 vehicle flow rate of 1,100 vehicles/hour, shift a given level of traffic noise with respect to the 1996 noise levels. These curves show the sound transmission loss at distances up to 40 m into Will Rogers Drive for the as-built street opening into the residential area. The measurement line is at a 15-m north offset distance from the center line of Will Rogers Drive, corresponding approximately to the front entrances of the two houses nearest FM 3009. Figure 5.4 shows similar changes in observed traffic noise levels at distances of up to 40 m into Cyrus McCormick Street.

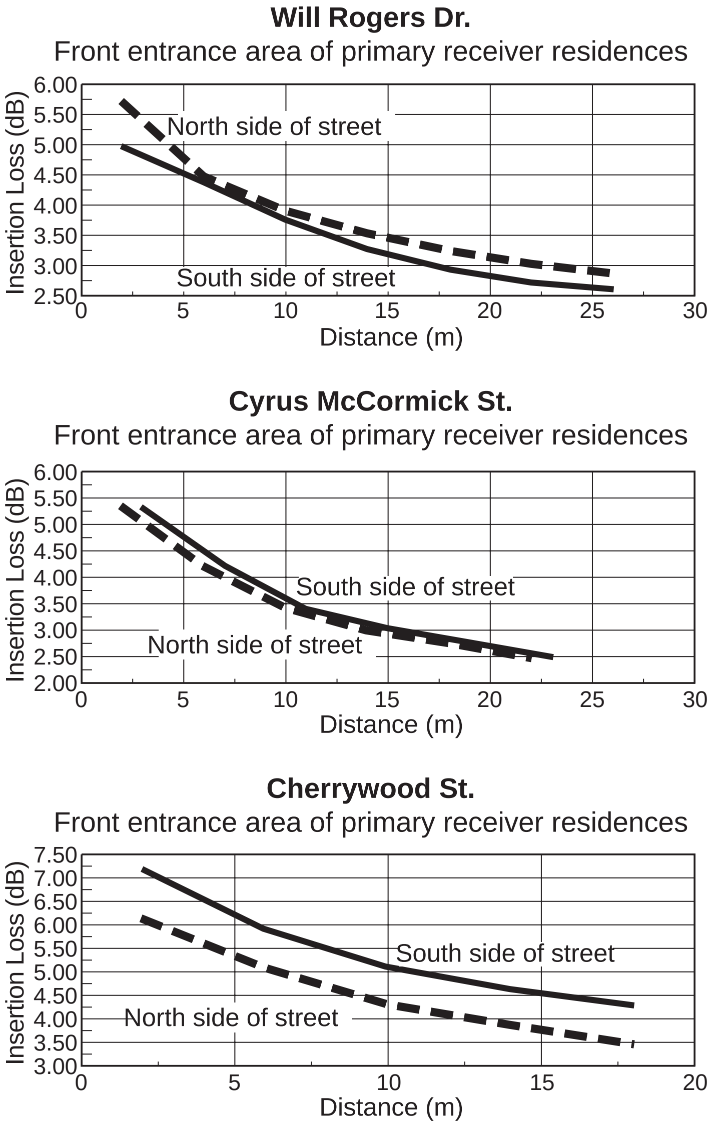


Figure 5.2 Computer model estimates of noise barrier insertion loss in front yards of primary receiver residences vs. width of barrier opening at entry streets

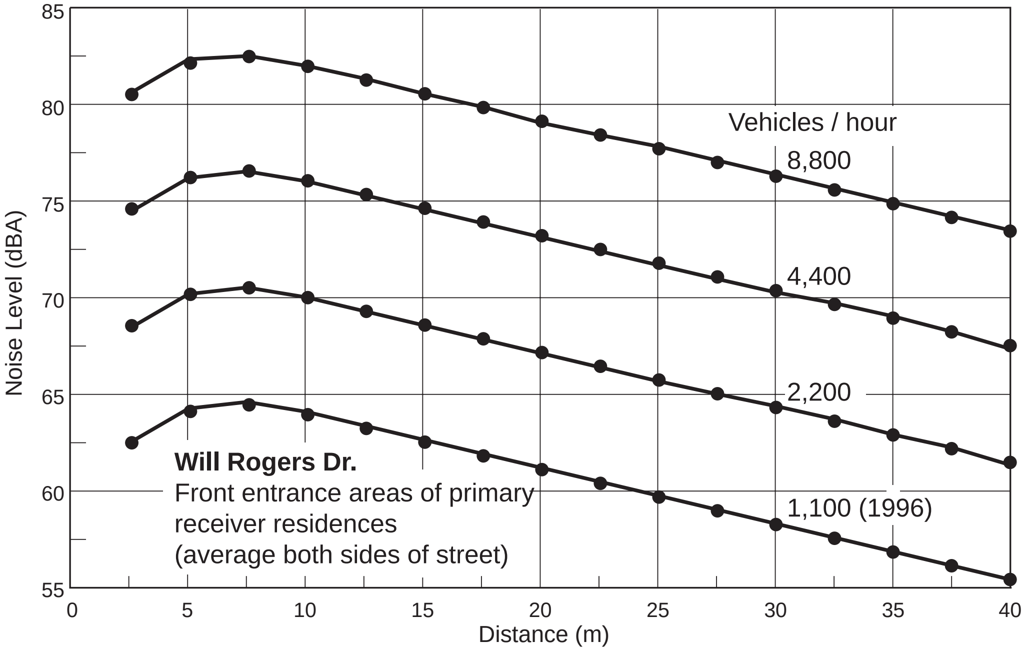


Figure 5.3 Reduction in noise barrier effectiveness at Will Rogers Drive vs. future traffic density of FM 3009

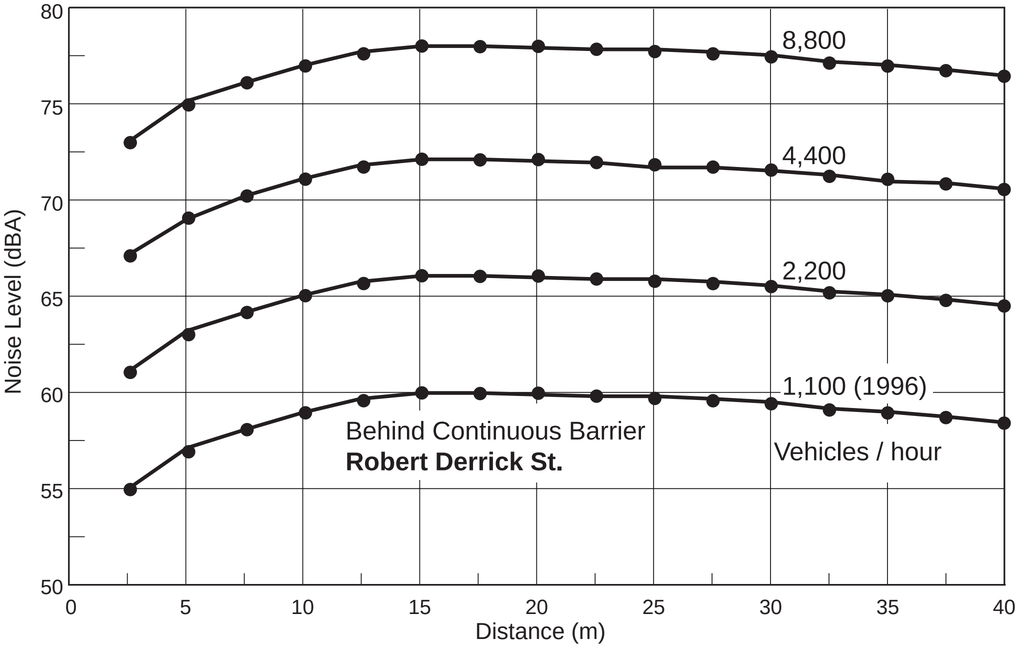


Figure 5.4 Reduction in noise barrier effectiveness on Robert Derrick Street vs. future traffic density of FM 3009

5.4 COMPUTER SIMULATION OF NOISE BARRIER PERFORMANCE

5.4.1 STAMINA

The original analysis for the design of the FM 3009 noise barrier was carried out by the TxDOT San Antonio District using STAMINA 2.0. STAMINA is the computer program most commonly used for predicting highway noise attenuation afforded by a barrier. It was developed for the FHWA by the acoustical consulting firm of Bolt, Beranek, and Newman, Inc. It is designed to model up to twenty roadways, up to ten barriers, and up to twenty receivers in a single run. It creates a data file for use by another program, OPTIMA, which determines the most effective barrier heights and lengths for the specified geometry. As many as eight barrier heights can be modeled using OPTIMA.

STAMINA is also the traffic noise prediction program most commonly used by state highway agencies, including TxDOT. Many states, including Texas, have developed input modules to facilitate the use of STAMINA. The major limitation of the STAMINA program stems from the limitations of computer hardware that prevailed at the time of its development. STAMINA was initially developed for use on mainframe computers, the only computers available at the time having the necessary computational power. Because mainframe computer time was expensive, STAMINA uses only a single frequency of 500 Hz rather than a representative noise source spectrum.

Highway traffic produces noise in the spectral range of 100 to 4,000 Hz. Trucks produce a noise frequency spectrum that differs from that of passenger cars. The attenuation of sound and the perceived annoyance of sound are frequency dependent. The decision (by STAMINA) to use the single 500-Hz frequency represents a good compromise between the most dominant traffic noise frequencies and the more annoying lower frequency noise. However, a single-frequency analysis has limitations in analyzing specific situations.

Traffic volumes in STAMINA 2.0 are based on design hourly volume (DHV). Usually, Level of Service C traffic volumes and associated roadway speeds are used to predict the worst-case scenario. From this information, STAMINA 2.0 calculates the equivalent sound pressure level L_{eq} (the constant sound level that would deliver the same sound energy as the given time-varying signal).

Three types of barriers can be modeled in STAMINA 2.0: absorptive, reflective, and structural. Other factors used by the model are “alpha factors” and “shielding factors.” Alpha factors describe the attenuation effects of hard or soft ground on noise propagation from the source to the receiver. Shielding factors account for additional noise attenuation associated with hard ground. When an earth berm is used, the predicted attenuation is increased by 3 dB owing to its soft-ground properties.

5.4.2 SoundPLAN

SoundPLAN is a very comprehensive computer noise simulation program having several different modules. One of the modules uses the same algorithms as STAMINA 2.0 to calculate traffic noise propagation and noise barrier effectiveness. The principal noise modeling module of SoundPLAN differs from STAMINA in that it uses a ray-tracing technique from the roadway source to the receiver locations. However, STAMINA and the SoundPLAN ray-trace results are essentially identical when using the input parameter limitations required by FHWA.

All of the field site test locations on FM 3009 were modeled using the SoundPLAN traffic noise simulation program. Although this study was limited in the amount of detail that could be employed in representing actual field conditions, the derived model results are in quite close agreement with the field measurements.

The SoundPLAN traffic noise model has the following features:

1. SoundPLAN performs receiver-to-source ray tracing to obtain minimum propagation path time. Calculation time versus accuracy optimization is user defined for grid noise map calculations.
2. SoundPLAN calculates grid receiver points that follow ground topography and includes user-defined receiver heights.
3. SoundPLAN can calculate up to five building occupancy levels for a single receiver location.
4. The following parameters are selectable in representing traffic vehicle noise source conditions: Vehicle numbers, traffic speed, road surface, traffic mix, and road gradient.

5. SoundPLAN can calculate multiple reflections for each reflecting surface specified (barriers, building walls, fences, etc.). Each reflector may be assigned a specific absorption coefficient.
6. SoundPLAN can calculate horizontal sound diffraction around vertical barrier edges and corners of buildings.

The SoundPLAN noise barrier design module has the following features:

1. Barrier optimization is calculated for multiple receiver locations.
2. Barrier dimensions are user defined as barrier panel elements.
3. Barrier element cost is user defined and stored for optimization of the barrier design, considering the barrier materials and construction costs.
4. Maximum and minimum barrier heights can be defined by the user prior to barrier optimization.
5. Barrier cost-performance diagrams can be presented for each receiver location.

With the FM 3009 site layout drawings of the three entry streets, the utility access alley, and a section of the continuous noise barrier at Robert Derrick Street entered into the program, the traffic noise levels at any of the sound level meter stations could be predicted for various measured or assumed traffic flow conditions. Figure 5.5 shows a noise contour map of FM 3009 calculated using SoundPLAN with the prevailing traffic flow conditions and without the noise barrier. Figure 5.6 shows a similar noise contour map with the FM 3009 as-built noise barrier in place.

The predicted sound level meter readings are in reasonable agreement with the experimental data, considering the simplified site details used in the model. In particular, the results for Will Rogers Drive are in very close agreement, insofar as the computer model of this site corresponds closely with the actual site. Although SoundPLAN is capable of generating complete noise level contour maps from prespecified grid layouts, its ability to predict certain specific noise level readings at the actual microphone stations was considered to be more representative of the computer model application on this project.

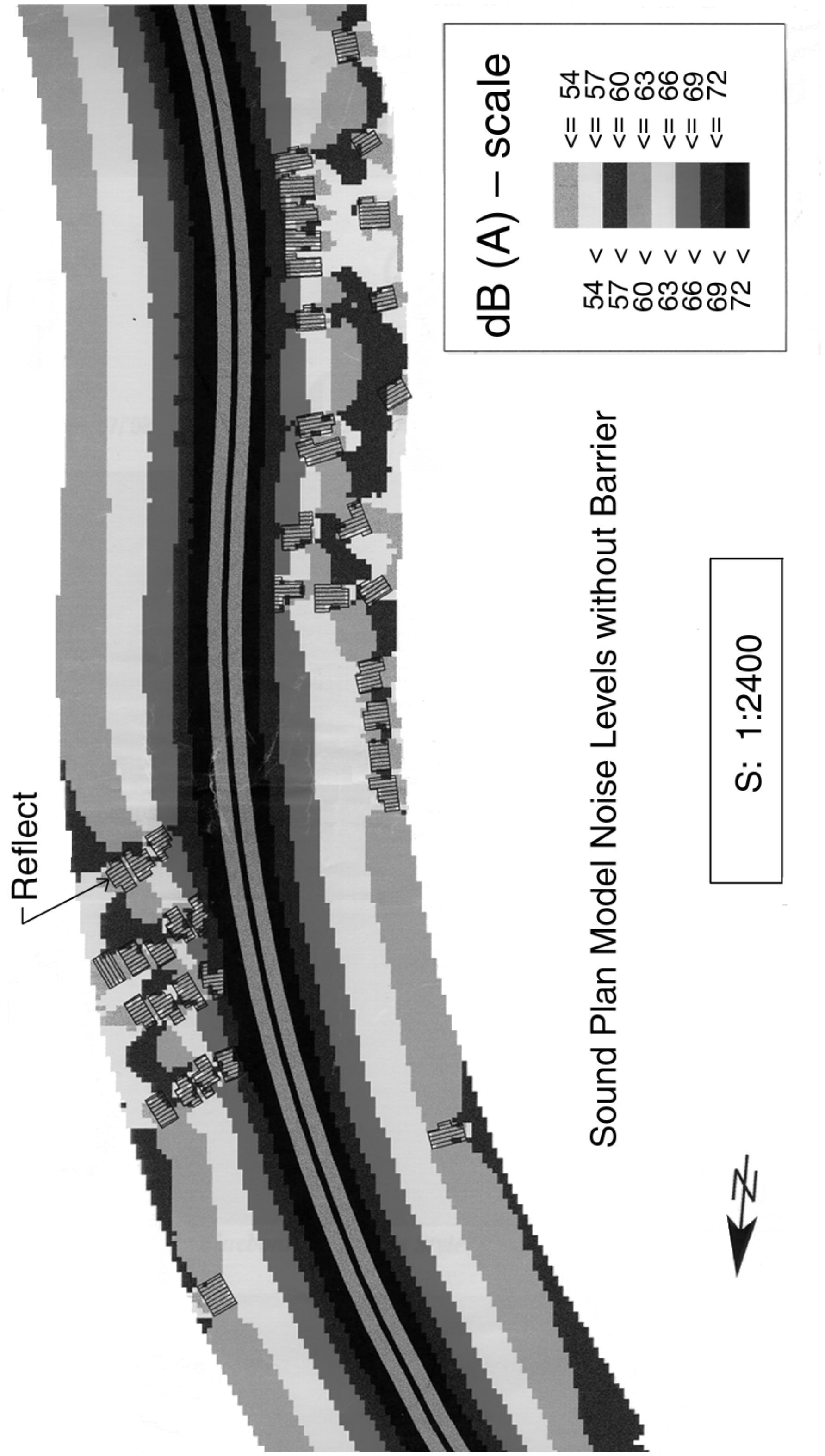


Figure 5.5 SoundPLAN model noise levels without barriers

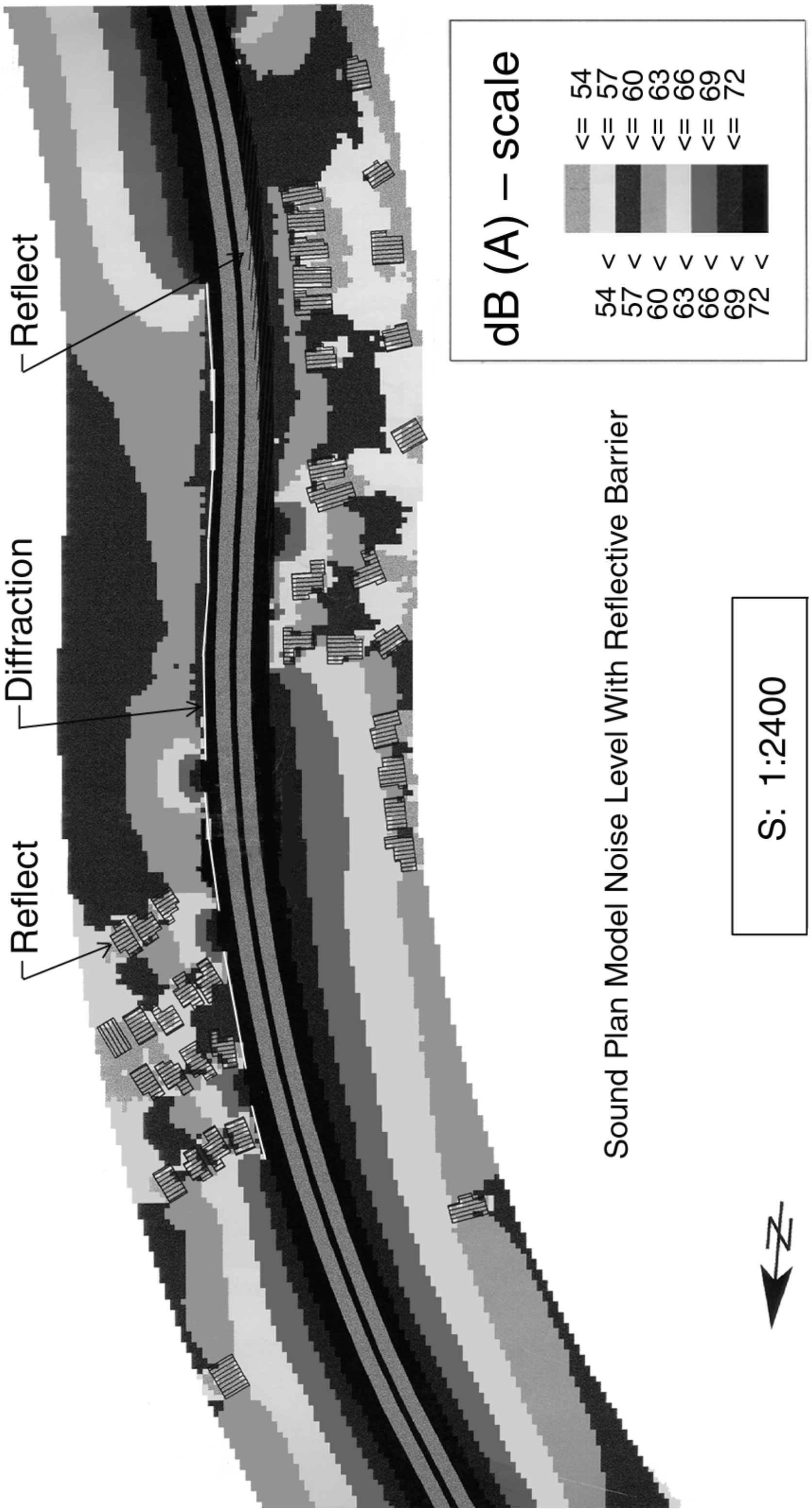


Figure 5.6 SoundPLAN model noise levels with reflective barrier along FM 3009

The SoundPLAN contour maps shown in Figures 4.8, 4.11, and 4.14 of the simulated noise levels at the entry streets along FM 3009 were produced using the same manual interpolation procedures applied in contouring the measured noise levels. In most cases, the predicted noise levels at the reference microphone station were within ±1 dB of the experimental values when the observed traffic densities were used in the model. Comparisons between the predicted and measured noise levels at greater distances into the entry streets and in the yards of the houses were within about 1 dB on Will Rogers Drive and on Cherrywood Street. The ground elevations on Cyrus McCormick Street available from the FM 3009 site schematic drawings were not sufficiently detailed to show the actual topography along the street or on the private properties facing the street. Consequently, the SoundPLAN predictions were in useful agreement with the measured noise levels only at the primary residences (accurate to within about 2 dB). By accounting for the down-slope and lower elevation of the street at distances greater than about 10 m into Cyrus McCormick Street, the predicted noise levels were much lower than the actual values measured along the street. A more exact model of ground elevations and the inclusion of representative reflecting fronts of several of the houses (located on elevated ground) would be required to properly apply SoundPLAN to the relatively complex local acoustical environment on Cyrus McCormick Street.

Traffic noise simulations were also computed for comparison with the noise measurements in the utility access alley and at the continuous noise barrier at Robert Derrick Street. The predicted sound transmission loss in the narrow, fence-lined alley was precisely accurate at all but one microphone station for a distance of more than 30 m into the alley. Additional predicted values in the backyards of the primary receiver residence and its two adjacent neighbors were in the range of 58–59 dBA, indicating reasonably low noise levels only 2 dB higher than those observed at similar distances behind the continuous noise barrier.

CHAPTER 6. CONCLUSIONS

6.1 OVERALL RESULTS

The field measurements and computer simulation modeling calculations performed for this project were successful in characterizing the effectiveness of the traffic noise barriers on FM 3009 and, in particular, in providing quantitative information on the degrading effects of street openings in the barriers.

6.2 SPECIFIC RESULTS

The project plan for evaluating the effectiveness of the traffic noise barriers constructed on FM 3009 in Schertz, Texas, involved several tasks and activities. In combination, these tasks and their procedures represent useful progress in characterizing traffic noise barriers and in conducting quantitative field measurements on traffic noise impacts within a specific residential subdivision. Given that the openings in the noise barriers at the streets entering the residential areas represented a special problem, the work focused on the issue of noise intruding through these openings. Conclusions concerning the specific tasks are presented below.

6.2.1 Community Opinion Survey of Traffic Noise

The residents of the Greenfield Village Subdivision on FM 3009 were surveyed by mail-in questionnaire to determine their subjective opinions on the effectiveness of the newly constructed noise barriers. The questionnaire was particularly successful in obtaining a meaningful response (65% return) from the area residents. In the survey, 70% of the primary receiver residences reported that the previously noted noise disturbances caused by large trucks has been reduced since the noise barriers were constructed. The majority opinion of the residents living closest to FM 3009 was that the noise barriers were noticeably beneficial to their home environment for reasons of noise reduction as well as for other reasons, such as improved security and safety and reduced wind-blown debris.

6.2.2 Noise Intrusion through Street Openings

Measurements of noise intrusion into the residential areas of Greenfield Village Subdivision provided quantitative information on the reduced noise abatement of the noise barriers in the vicinity of the street openings. The continuous noise barriers on each side of FM 3009 are very effective in reducing the traffic noise, with a typical insertion loss in the range of 8–12 dB, depending on the receiver position behind the barrier. However, the street openings (16.5 m, 21.3 m, and 25.6 m on the streets tested) reduce the barrier insertion loss by 3–6 dB at positions in the front yards of the primary receiver residences. For practical street openings wider than about 10 m, this reduction in noise abatement is more dependent on the primary receiver observation position (relative to the end of the nearest noise barrier panel) than on the actual width of the street opening. In comparison, for barrier openings smaller than that required for a street, such as at the 4.6-m-wide utility access alley, the insertion loss is reduced by only 2–3 dB below that of the continuous barrier. These field observations have been duplicated with reasonable accuracy using SoundPLAN computer simulation, indicating that preliminary estimates of such noise intrusion effects could be evaluated prior to final placement and specification of the barrier.

6.2.3 Noise Barrier Effectiveness

The noise barriers on FM 3009 provide the minimum traffic noise abatement required by TxDOT noise guidelines. The insertion loss occurring along continuous sections of the barrier walls measured 8–12 dB. This value compared favorably with an insertion loss of 12 dB predicted when the measured traffic density on FM 3009 was used in the SoundPLAN computer model. By contrast, the street openings into the Greenfield Village Subdivision on FM 3009 degrade the performance of the noise barriers to a significant degree. These openings were found to reduce the insertion loss at the primary receiver locations by as much as 3–6 dB, depending on the width of the barrier opening and on the particular primary receiver observation position. The design-year effectiveness of the noise barriers is, therefore, reduced because of the street openings.

The findings of this research study indicate that street openings in traffic noise barriers can be quantitatively characterized in terms of the noise impact on the primary receiver residences. The consequence of street openings into residential areas is a localized reduction of the noise barrier insertion loss. This project has provided valuable insight into the technical nature of sound intrusion through street openings and has demonstrated that computer simulations aimed at forecasting future intrusion noise levels at such sites can be performed and relied upon with confidence to provide practical results.

6.2.4 Computer Modeling Results

Computer simulation results obtained by using representative FM 3009 site conditions in SoundPLAN for each of the tested street openings predicted the noise intrusion levels at the primary residence locations within about 1 dB. Computer simulations of the traffic noise at greater distances into the residential areas were within about 2 dB of the experimental measurements at those entry streets where the simplified model used in SoundPLAN was in acceptable agreement with the actual site conditions. For cases in which SoundPLAN modeling did not contain accurate details on private property ground elevations or reflections and absorption caused by particular house structures and shrubbery, such as was the case on Cyrus McCormick Street, the simulated results were less noisy by 5–6 dB compared with the measured field values.

SoundPLAN modeling was also applied to simulate the noise intrusion through the relatively narrow utility access alley for comparison with measured noise levels. In this case, the calculated and measured values compared very well. Computer model predictions of traffic noise levels in the backyards of one of the primary residences and its two adjacent neighbors were only approximately 2 dB higher than that predicted for similar positions behind a continuous noise barrier.

6.2.5 Heavy Truck Acceleration Noise

A practical noise model for representing the traffic noise of individual moving truck vehicles was developed and tested as an aid in characterizing the noise observed at curbside observation points. The model was demonstrated to be accurate in representing a single truck pass-by event, taking into account its speed and acceleration. Although this acceleration noise test was limited only to observations of vehicles of opportunity, the resulting model appears to offer a useful approach by which further studies of truck acceleration noise can be conducted. This modeling effort is important to the traffic noise conditions on FM 3009, given that events of this type were responsible for several of the original complaints that led to the construction of the noise barriers.

APPENDIX A

TRAFFIC NOISE COMMUNITY OPINION SURVEY

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TRAFFIC NOISE COMMUNITY OPINION SURVEY

A.1 Purpose of Opinion Survey

An opinion survey was conducted in the Greenfield Village Subdivision of Schertz, Texas, to gather subjective viewpoints from the residents on the effectiveness of the recently constructed traffic noise barrier on FM 3009. Of primary concern in this survey was the degree to which the barrier reduced noise disturbances caused by large trucks. The survey was also designed to provide information on the degree of traffic noise annoyance experienced before and after construction of the barrier and to obtain comments on noise barrier effects on the appearance of the residential area.

A.2 Survey Methodology

The survey questionnaire consisted of eight principal questions developed from similar published traffic noise investigations (Refs a.2 – a.7)*. The questions were designed to ensure a high percentage of completed responses and to minimize any bias toward answers that might be introduced by the way the questions were worded. The survey concentrated primarily on barrier performance in mitigating traffic noise.

The survey questions included single and multiple responses. The single-choice questions (yes/no) addressed the noise barrier's effectiveness. The multiple-choice questions solicited a wider range of responses and different degrees of opinion. A specimen of the finalized questionnaire distributed to the Greenfield Village Subdivision is presented in Figure A-1. Questions 2 through 9 in the questionnaire were used in the analysis.

The questionnaires were distributed by mail to the area residents in early March 1996. The names and addresses were obtained from the most recent issue of Cole's Directory (Ref a.1). Each questionnaire was personalized with the name and address of the resident for data analysis purposes. Each resident received a questionnaire, a stamped return-addressed envelope for use in mailing back the questionnaire by the end of March 1996, and a brief letter explaining the survey purpose and identifying the UTSA project team members. Of the 289 questionnaires mailed to residents, 160 were returned, representing a 55% participation rate. Follow-up contacts were made by telephone to those who did not respond to determine whether a second mailing might improve participation. Duplicate questionnaires were mailed to sixty residents who agreed to respond, boosting the final participation to approximately 60%.

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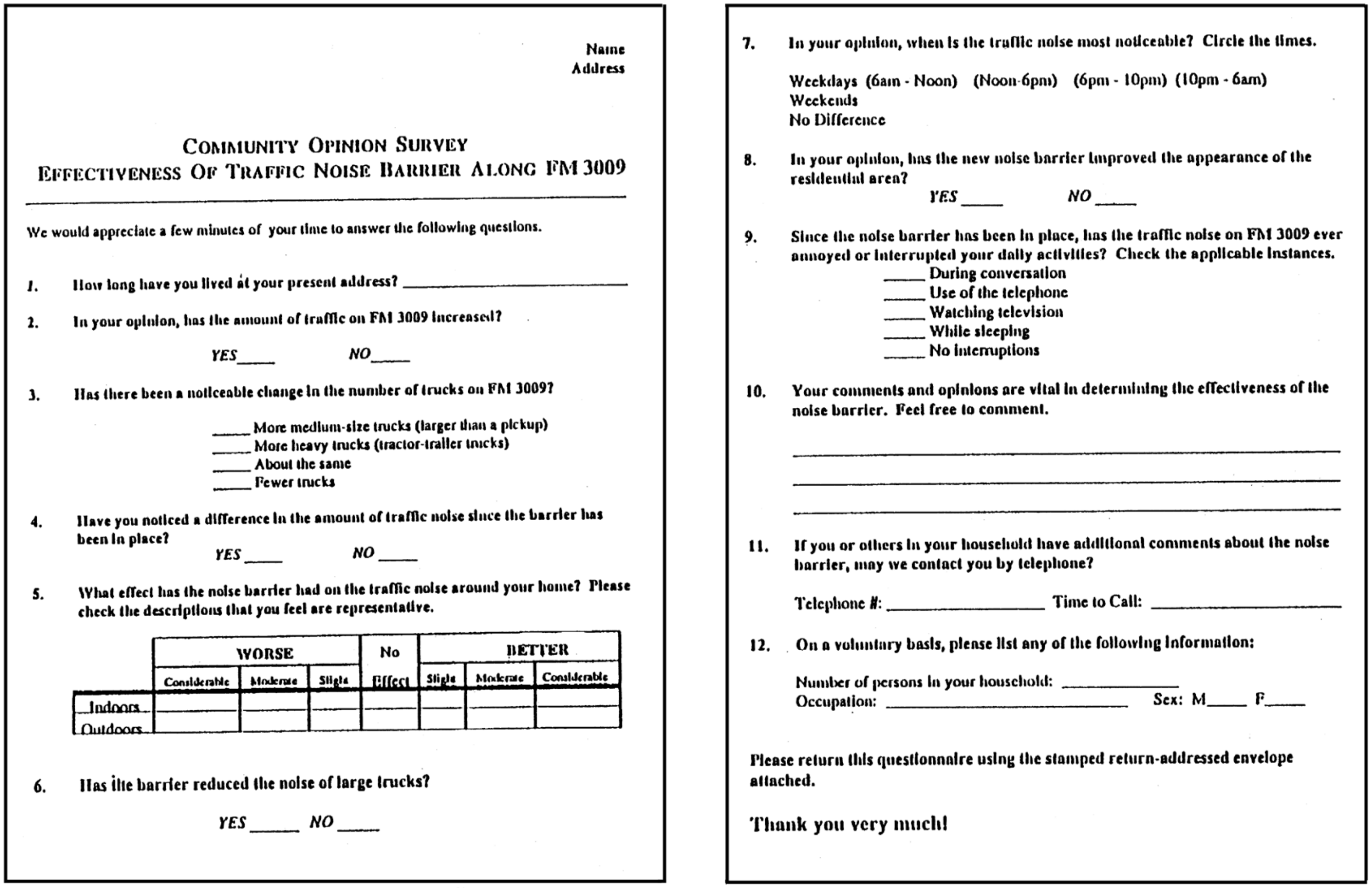
[*] References appear at the end of Appendix A.



Name
Address

COMMUNITY OPINION SURVEY
EFFECTIVENESS OF TRAFFIC NOISE BARRIER ALONG FM 3009

We would appreciate a few minutes of your time to answer the following questions.

1. How long have you lived at your present address? ____________________

2. In your opinion, has the amount of traffic on FM 3009 increased?

   *YES*____ *NO*____

3. Has there been a noticeable change in the number of trucks on FM 3009?

   ____ More medium-size trucks (larger than a pickup)
   ____ More heavy trucks (tractor-trailer trucks)
   ____ About the same
   ____ Fewer trucks

4. Have you noticed a difference in the amount of traffic noise since the barrier has been in place?

   YES ____ *NO* ____

5. What effect has the noise barrier had on the traffic noise around your home? Please check the descriptions that you feel are representative.

	WORSE			No	BETTER		
	Considerable	Moderate	Slight	Effect	Slight	Moderate	Considerable
Indoors							
Outdoors							

6. Has the barrier reduced the noise of large trucks?

   YES _____ *NO* ____

7. In your opinion, when is the traffic noise most noticeable? Circle the times.

   Weekdays (6am - Noon) (Noon-6pm) (6pm - 10pm) (10pm - 6am)
   Weekends
   No Difference

8. In your opinion, has the new noise barrier improved the appearance of the residential area?

   YES _____ *NO* _____

9. Since the noise barrier has been in place, has the traffic noise on FM 3009 ever annoyed or interrupted your daily activities? Check the applicable instances.

   ____ During conversation
   ____ Use of the telephone
   ____ Watching television
   ____ While sleeping
   ____ No interruptions

10. Your comments and opinions are vital in determining the effectiveness of the noise barrier. Feel free to comment.

    ____
    ____
    ____

11. If you or others in your household have additional comments about the noise barrier, may we contact you by telephone?

    Telephone #: ________________ Time to Call: ________________

12. On a voluntary basis, please list any of the following information:

    Number of persons in your household: ____________
    Occupation: ________________________ Sex: M____ F____

Please return this questionnaire using the stamped return-addressed envelope attached.

Thank you very much!

Figure A.1 Specimen of Community Traffic Noise Survey for Greenfield Village Subdivision, Schertz, Texas

A.3 Tabulation and Compilation of Data

Data entry and initial compilation were performed for all of the survey responses. Upon examination of the results, the decision was made to narrow the final data analysis to those area residences located within approximately 180 m of the FM 3009 centerline. This selected coverage permitted a more thorough description of the perceived effectiveness of the noise barrier by these residents most directly susceptible to the traffic noise. This area was then subdivided into two categories: primary and secondary receivers. Primary receivers are the residences located immediately adjacent to the noise barrier. Secondary receivers are all other residences located laterally behind the noise barrier and within a distance of approximately 180 m from the FM 3009 centerline. Table A.1 lists the breakdown of the percentages of the survey respondents in both receiver categories and for all residents in the selected area.

Table A.1 Survey Responses by category from Greenfield Village Subdivision, Schertz, Texas

Street Names	Number of Houses	Ratio of Responses	Percentage of Responses
PRIMARY RECEIVERS			
Cedarwood	3	2 of 3	67%
Cherrywood	2	2 of 2	100%
Cyrus McCormick	2	2 of 2	100%
Eli Whitney	2	2 of 2	100%
Patrick Henry	1	1 of 1	100%
Robert Derrick	18	14 of 18	78%
Spicewood	3	2 of 3	67%
Will Rogers	1	0 of 1	0%
TOTAL PRIMARY	**32**	**25 of 32**	**78.13%**
SECONDARY RECEIVERS			
Cedarwood	2	2 of 2	100%
Cherrywood	3	0 of 3	0%
Cyrus McCormick	14	4 of 14	79%
Dearborn	8	7 of 8	88%
Eli Whitney	9	5 of 10	50%
Greenwood	19	13 of 20	65%
Henry Ford	8	4 of 8	50%
Patrick Henry	8	6 of 8	75%
Spicewood	8	3 of 8	38%
Webster Drive	11	9 of 11	82%
Will Rogers	8	4 of 8	50%
TOTAL SECONDARY	**98**	**64 of 100**	**65.31%**
TOTAL ALL	**130**	**89 of 132**	**67.42%**

A standard spreadsheet was used for data entry and compilation (Microsoft Excel 5.0). Table A.2 presents the compiled percentage results for each of the chosen eight survey questions. This table is divided into primary and secondary receiver category areas, with the percentages listed by street. The percentage results for each question were used to create graphs displaying the distribution of the responses (Figures 3.1 through 3.6 in the text of this report).

The graphs displaying responses to Questions 3, 5, and 7 contain data representing multiple-answer responses. The percentages for these responses will not necessarily equal 100%. For example, Question 3 (Has there been a noticeable change in the amount of trucks?), with answer choices of "Same/ Medium/ Heavy," had significant responses of *both* "Medium" and "Heavy" from many respondents. The graphic display presents every response indicating "Medium" and every response indicating "Heavy," resulting in a final figure that exceeds 100%. In addition, Question 7 is supplemented by two composite choices not provided in the questionnaire. This is owing to the significant response in multiple-answer choices of "6a.m.–noon and noon–6p.m." or "6p.m.–10p.m. and 10p.m.–6a.m." In summarizing these data, the supplemental choices are merged and referred to as "Daytime" and "Nighttime," respectively.

By including a "Comments" space, the questionnaire provided an opportunity for the residents to express their opinion on the effectiveness and desirability of the traffic noise barrier. Approximately 75% of the residents returned write-in comments. Thirty-three percent of the participants commented that the barrier performance exceeded their expectations. The barrier was also said to provide secondary benefits not related to noise abatement, including security, a noticeable decrease in the presence of dust and debris, and improved water drainage. Approximately 10% of the write-in respondents stated that they strongly opposed the barrier for various reasons. Negative remarks from this group included comments on the wasteful spending of taxpayers' money, creation of a prison-like atmosphere, and excessive barrier height.

REFERENCES — APPENDIX A

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STREET NAME	Question No. 2 *YES*	Question No. 3 *SAME*	Question No. 3 *MEDIUM*	Question No. 3 *HEAVY*	Question No. 4 *YES*	Question No. 5 *CONSIDERABLY BETTER*	Question No. 5 *MODERATELY BETTER*	Question No. 5 *SLIGHTLY BETTER*
PRIMARY RECEIVERS*								
Cedarwood	67%	33%	67%	33%	67%	67%	0%	0%
Cherrywood	100%	0%	50%	100%	100%	100%	0%	0%
Cyrus McCormick	100%	50%	0%	50%	100%	50%	50%	0%
Eli Whitney	100%	50%	50%	50%	50%	0%	50%	0%
Robert Derrick	72%	22%	44%	50%	56%	39%	17%	11%
Spicewood	67%	0%	67%	67%	67%	33%	33%	0%
Patrick Henry	100%	0%	100%	100%	100%	100%	0%	0%
Will Rogers	0%	0%	0%	0%	0%	0%	0%	0%
AVERAGE	76%	19%	47%	56%	67%	49%	19%	1%
SECONDARY RECEIVERS								
Cedarwood	100%	0%	100%	50%	100%	100%	0%	0%
Cherrywood	0%	0%	0%	0%	0%	0%	0%	0%
Cyrus McCormick	71%	21%	21%	57%	50%	29%	14%	0%
Dearborn	88%	0%	63%	75%	63%	25%	13%	13%
Eli Whitney	56%	0%	33%	44%	11%	11%	11%	11%
Greenwood	68%	5%	21%	42%	37%	32%	5%	5%
Henry Ford	50%	0%	38%	38%	25%	13%	0%	0%
Spicewood	25%	0%	13%	38%	25%	13%	0%	13%
Patrick Henry	75%	13%	63%	25%	13%	0%	13%	0%
Webster Dr.	82%	9%	45%	73%	55%	18%	9%	18%
Will Rogers	50%	13%	13%	38%	38%	13%	13%	13%
AVERAGE	62%	5%	36%	46%	33%	15%	8%	9%

---

* Primary receivers are those residences located immediately adjacent to the noise barrier. Refer to Figure A-1 for detailed questions.

STREET NAME	Question No. 5 *NO EFFECT*	Question No. 5 *SLIGHTLY WORSE*	Question No. 5 *MODERATELY WORSE*	Question No. 5 *CONSIDERABLY WORSE*	Question No. 5 *CONSIDERABLY BETTER*	Question No. 5 *MODERATELY BETTER*	Question No. 5 *SLIGHTLY BETTER*
PRIMARY RECEIVERS*							
Cedarwood	0%	0%	0%	0%	67%	0%	0%
Cherrywood	0%	0%	0%	0%	100%	0%	0%
Cyrus McCormick	0%	0%	0%	0%	50%	50%	0%
Eli Whitney	50%	0%	0%	0%	50%	0%	0%
Robert Derrick	6%	6%	0%	0%	33%	22%	11%
Spicewood	0%	0%	0%	0%	33%	33%	0%
Patrick Henry	0%	0%	0%	0%	0%	100%	0%
Will Rogers	0%	0%	0%	0%	0%	0%	0%
AVERAGE	7%	1%	0%	0%	42%	26%	1%
SECONDARY RECEIVERS							
Cedarwood	0%	0%	0%	0%	50%	50%	0%
Cherrywood	0%	0%	0%	0%	0%	0%	0%
Cyrus McCormick	29%	0%	0%	0%	36%	7%	7%
Dearborn	38%	0%	0%	0%	25%	25%	13%
Eli Whitney	11%	0%	0%	0%	0%	11%	22%
Greenwood	26%	0%	0%	0%	16%	21%	16%
Henry Ford	0%	0%	0%	0%	0%	13%	0%
Spicewood	13%	0%	0%	0%	0%	13%	25%
Patrick Henry	50%	0%	0%	0%	0%	13%	13%
Webster Dr.	18%	0%	0%	0%	27%	27%	9%
Will Rogers	13%	0%	0%	0%	13%	25%	0%
AVERAGE	21%	0%	0%	0%	10%	18%	12%

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* Primary receivers are those residences located immediately adjacent to the noise barrier. Refer to Figure A-1 for detailed questions.

STREET NAME	Question No. 5 *NO EFFECT*	Question No. 5 *SLIGHTLY WORSE*	Question No. 5 *MODERATELY WORSE*	Question No. 5 *CONSIDERABLY WORSE*	Question No. 6 *YES*	Question No. 7 *6AM - NOON*	Question No. 7 *NOON - 6PM*	Question No. 7 *6PM - 10PM*
PRIMARY RECEIVERS*								
Cedarwood	0%	0%	0%	0%	67%	33%	0%	33%
Cherrywood	0%	0%	0%	0%	100%	50%	0%	0%
Cyrus McCormick	0%	0%	0%	0%	100%	50%	0%	50%
Eli Whitney	50%	0%	0%	0%	50%	50%	0%	0%
Robert Derrick	6%	0%	0%	6%	67%	11%	17%	22%
Spicewood	0%	0%	0%	0%	67%	0%	33%	0%
Patrick Henry	0%	0%	0%	0%	100%	50%	0%	50%
Will Rogers	0%	0%	0%	0%	0%	0%	0%	0%
AVERAGE	7%	0%	0%	1%	69%	31%	6%	19%
SECONDARY RECEIVERS								
Cedarwood	0%	0%	0%	0%	100%	0%	0%	0%
Cherrywood	0%	0%	0%	0%	0%	0%	0%	0%
Cyrus McCormick	21%	0%	0%	0%	43%	7%	0%	7%
Dearborn	25%	0%	0%	0%	75%	38%	0%	25%
Eli Whitney	11%	11%	0%	0%	33%	22%	11%	0%
Greenwood	11%	0%	0%	0%	58%	21%	26%	5%
Henry Ford	25%	0%	0%	0%	13%	13%	0%	0%
Spicewood	0%	0%	0%	0%	25%	25%	0%	0%
Patrick Henry	38%	0%	0%	0%	13%	25%	0%	13%
Webster Dr.	9%	9%	0%	0%	36%	18%	0%	36%
Will Rogers	13%	0%	0%	0%	38%	0%	13%	25%
AVERAGE	16%	3%	0%	0%	36%	20%	6%	13%

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* Primary receivers are those residences located immediately adjacent to the noise barrier. Refer to Figure A-1 for detailed questions.

STREET NAME	Question No. 7 *10PM - 6AM*	Question No. 7 *DAY*	Question No. 7 *NIGHT*	Question No. 7 *WEEKEND*	Question No. 7 *NO DIFFERENCE*	Question No. 8 *YES*	Question No. 9 *NO INTERRUPTIONS*	Question No. 9 *DAILY ACTIVITIES*
PRIMARY RECEIVERS*								
Cedarwood	0%	0%	33%	33%	0%	67%	67%	0%
Cherrywood	0%	0%	0%	0%	0%	100%	100%	0%
Cyrus McCormick	0%	0%	0%	0%	0%	100%	100%	0%
Eli Whitney	0%	50%	0%	0%	0%	50%	50%	50%
Robert Derrick	0%	11%	0%	0%	17%	56%	61%	17%
Spicewood	0%	33%	0%	33%	0%	67%	67%	0%
Patrick Henry	0%	0%	0%	0%	0%	100%	100%	0%
Will Rogers	0%	0%	0%	0%	0%	0%	0%	0%
AVERAGE	0%	12%	4%	8%	2%	67%	68%	8%
SECONDARY RECEIVERS								
Cedarwood	0%	50%	0%	0%	50%	100%	0%	100%
Cherrywood	0%	0%	0%	0%	0%	0%	0%	0%
Cyrus McCormick	0%	29%	0%	0%	29%	43%	71%	7%
Dearborn	0%	25%	0%	0%	0%	50%	88%	0%
Eli Whitney	0%	0%	0%	0%	22%	22%	33%	22%
Greenwood	0%	0%	0%	5%	21%	32%	58%	11%
Henry Ford	0%	13%	0%	0%	25%	25%	25%	13%
Spicewood	0%	0%	0%	0%	0%	13%	38%	0%
Patrick Henry	0%	0%	0%	0%	13%	13%	63%	0%
Webster Dr.	0%	18%	0%	0%	27%	45%	73%	9%
Will Rogers	0%	0%	0%	0%	0%	25%	50%	0%
AVERAGE	0%	7%	0%	1%	14%	28%	53%	7%

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* Primary receivers are those residences located immediately adjacent to the noise barrier. Refer to Figure A-1 for detailed questions.

APPENDIX B

TRAFFIC FLOW DATA — FM 3009

APPENDIX B

TRAFFIC FLOW DATA — FM 3009

Appendix B presents traffic flow measured on FM 3009 in reference to the experimental traffic noise measurements, including the methodology, measurements, and related reference information.

B.1 Video Traffic Flow Measurement

It was necessary to measure traffic flow on FM 3009 in order to obtain complete information on the observed vehicle source noise levels and their correlation with the sound level measurements. In addition, accurate traffic flow measurements are needed for use in the computer simulation studies. An efficient approach to such comprehensive traffic flow measurements is one based on videotape records of the roadway, which, by suitable replay observations, can yield accurate counts of vehicles by category (auto, trucks, cycles), lane locations, direction, and average speeds. A video camera equipped with a date and time stamp captioned on the tape also allows the traffic observations to be accurately keyed to the sound level measurements of interest. The use of videotape recordings on FM 3009 allowed the traffic observations to be obtained without requiring us to count the cars and trucks traveling in each lane. Audio data recorded on the videotapes can be used in recognizing nontraffic noise sources, such as jet aircraft noise. Although average traffic noise levels are of principal interest, time synchronization between the video records and the sound level meters is important for accurate diagnosis of all sources of noise.

The equipment used for the traffic flow measurements consisted of a video camcorder, a camera tripod, and videotapes. The video camera was a Panasonic Model AG-188U VHS video camcorder. Power for the video camera included a rechargeable battery having an operating life of approximately 2 hours and an AC adapter. The videotape was Scotch High Standard T-120 and Kodak Highgrade T-160 extended length. The video camera operates only at standard tape speed; therefore, the recording times were 2 hours for T-120 tapes and 2 hours 40 minutes for T-160 tapes. Playback of traffic flow was performed on a four-head JVC model HR-D720U VCR.

B.2 Traffic Flow Data

Comprehensive evaluation of traffic flow can be time consuming. Techniques for improving the efficiency of viewing the video records include the use of two counting devices (one for cars and one for trucks) and a variable-speed VCR. The two counting devices are employed to ensure an efficient and accurate count of vehicles without shifting vision away from the video. A variable-speed VCR is useful in reducing the observation time. To obtain accurate vehicle counts and to minimize the video observation time, each lane is analyzed for cars and trucks during separate video replays.

The traffic flow data in Tables B.1 and B.2 were developed by reviewing the video records for the times listed in Table B.2. Table B.1 shows a breakout of selected vehicle counts and lane occupancy as derived from the video records. The columns in Table B.1 list the count of autos (A.1, A.2, A.3, A.4) and the count of trucks (T.1, T.2, T.3, T.4) in each lane. When observing the Greenfield Village Subdivision from the Live Oak Road intersection to Elbel Road (south direction), the lanes are numbered (1-4) left to right. The data listed in each column of Table B.1 represent the projected reference traffic volume (vehicle/hour) for cars and trucks for use in the SoundPLAN modeling studies. The columns titled "Total Autos" and "Total Trucks" in Table B.2 list the total projected traffic volumes (vehicle/hour) for cars and trucks in all lanes combined. The time intervals listed in Tables B.1 and B.2 are time intervals corresponding directly with the 10-minute recordings of the sound level meters.

Table B.1 Projected reference traffic volume (vehicle/hour) on FM 3009

Street & Date	Time	A-1	T-1	A-2	T-2	A-3	T-3	A-4	T-4
Cyrus McCormick	1630-1640	258	18	390	0	318	18	150	0
5/17/96									
Will Rogers	0640-0650	198	0	204	0	144	0	372	0
5/20/96									
Cherrywood	0644-0654	234	18	222	6	216	0	390	0
5/22/96									
Robert Derrick	0713-0723	216	42	246	6	192	0	588	12
5/23/96									
Robert Derrick	0910-0920	60	48	150	18	36	0	198	18
5/23/96									

Table B.2 Projected traffic volume (vehicle/hour)

Street & Date	Time	Total Autos	Total Trucks
Cyrus McCormick 5/17/96	0653-0706	1254	42
	0734-0744	1194	66
	1630-1640	1116	36
	1644-1654	1362	36
	1710-1720	1218	30
	1722-1732	1350	24
	1750-1800	1026	18
	1802-1812	1044	18
Will Rogers 5/20/96	0640-0650	918	0
	0654-0704	1020	42
	0715-0725	1440	78
	0728-0738	1194	42
	0755-0805	1056	48
	0808-0818	1098	24
	0830-0840	690	54
Will Rogers 5/20/96	1650-1700	1092	30
	1702-1712	1260	42
	1725-1735	1128	30
	1738-1748	1116	6
	1800-1810	900	18
	1815-1825	846	0
Cherrywood 5/22/96	0644-0654	1062	24
	0710-0720	1362	108
	0722-0732	1248	48
	0800-0810	1008	66
	0813-0823	1104	30
	1635-1645	1116	48
	1650-1700	1092	54
	1715-1725	1290	30
	1755-1805	1056	24
	1727-1737	1308	42
Robert Derrick 5/23/96	0713-0723	1242	60
	0750-0800	1218	48
	0811-0821	954	24
	0840-0850	630	60
	0910-0920	444	84

	Total Autos	Total Trucks
Average	1096 veh/hr.	39.8 veh/hr

B.3 Velocity Measurement

The average velocity of vehicles traveling on FM 3009 was derived from the video records. First, the distance (*D*) between two visual landmarks on the opposite side of the roadway from the camera location was measured. Second, the distance (L_i) from the camera to the center of the i^{th} lane was measured. Third, the distance from the camera to the line connecting the two landmarks (*L*) at a point directly on the opposite side of the roadway was measured. The speed of vehicles traveling in the selected lane is derived from the landmark distance spacing and the lane geometry described above combined with measurements of the observed vehicle travel times (*t*) when traveling between the landmarks in the video records. This technique is illustrated in Figure B.1. The average vehicle speed is calculated using the formula:

$$v = \frac{\frac{L_i}{L} * D}{t} \qquad \text{(Eq B.1)}$$

The distance between the two visual landmarks was selected to be greater than 380 ft. so that the videotape observations of typical vehicle travel times in lane 4 would be in the range of 4-6 seconds. The average speed of vehicles traveling in the farthest lane (lane 4) were derived in detail using the method explained above. The speed of vehicles traveling in the other lanes was checked and found to be nearly the same as that of vehicles traveling in lane 4. The results of the average speed determined for vehicles in lane 4 are listed in Table B.3. The times listed in Table B.3 correspond with the 10-minute recording times of the sound level meters.

Table B.3 Average vehicle velocity (mph)

Street & Date	Time	Average velocity (mph)	Number of vehicles
Will Rogers	0640-0650	50.55	31
5/20/96	0808-0818	53.33	39
	1650-1700	56.57	42
	1725-1735	54.63	37
Cherrywood	0644-0654	54.18	64
5/22/96	0813-0823	56.95	58
	1650-1700	55.12	26
	1727-1737	56.03	38

B.4 Mathematical Model for Vehicle Acceleration Noise

A practical mathematical model of the observed noise generated by an accelerating vehicle passing a roadside observation point was developed based on several simplifying assumptions characterizing the vehicle operation and travel path. With reference to Figure B.1, the model scenario and definition of terms include the following:

(1) A noisy vehicle starts at a traffic signal position (x=0, t=0) from a standing start (v=0) and advances along a straight line path at a constant acceleration (a_o).

(2) Three sound level meters (M3, M2, M1) are located at distances x_3, x_2, x_1 from the traffic signal, with each meter spaced at distance, d_3, d_2 , d_1, respectively, away from the vehicle path (M3 is closest to the traffic signal).

(3) At each distance, x_3, x_2, x_1 , the vehicle is at the closest point of approach (CPA) to the respective sound level meter and is assumed to exhibit the maximum observed noise level at that point. Times t_3, t_2, t_1, are the reference times for the vehicle pass-by event at each CPA.

(4) The distance at which the vehicle reaches steady roadway speed is $x=x_m$ and the corresponding time is $t=t_m$.

(5) The time-dependent slant distances between the moving vehicle and each sound level meter are defined as $R_3(t)$, $R_2(t)$, $R_1(t)$, respectively.

(6) The time-dependent sound level recorded by each sound level meter is defined as $A_3(t)$, $A_2(t)$, $A_1(t)$, respectively, and is assumed to obey a spherical-wave geometrical spreading law.

(7) The reference noise source level of the vehicle at each CPA is L_3, L_2, L_1, respectively.

(8) An average background noise level of 60.5 dBA (typical of actual field conditions) is assumed to exist at each sound level meter station during the vehicle observation time interval.

The time-dependent speed and position of the vehicle along the straight-line travel path may be expressed in terms of the acceleration as:

$$v(t) = \int_0^t a_o \, dt = a_o \, t \qquad \text{(Eq B.2)}$$

and

$$x(t) = \int_0^t a_o\, t\, dt = a_o\, t^2 \qquad \text{(Eq B.3)}$$

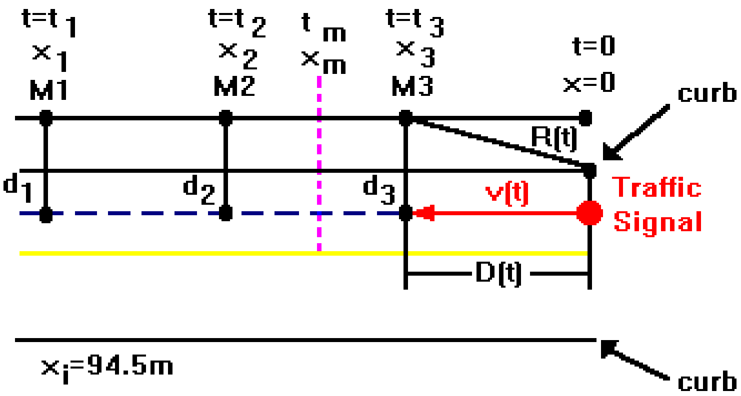

Figure B.1 Geometric layout and definition of symbols used in heavy vehicle acceleration noise model

As the vehicle travels from the starting point toward each CPA, the closing distance may be expressed as:

$$D_i(t) = x(t_i) - x(t)$$

$$= \frac{a_o}{2}(t_m^{\ 2} - t^2);\ \ i = 1, 2, 3 \qquad \text{(Eq B.4)}$$

When the time variable is referenced to the time, t_i, at which the vehicle is at the CPA,

$$D_i(t) = a_o\, t_i\,(t_i - t) - \frac{a_o}{2}(t_i - t)^{\,2};\ \ i=1, 2, 3 \qquad \text{(Eq B.5)}$$

The general form of the slant distance from the vehicle to the sound level meter is

$$R_i = \sqrt{d_i^{\ 2} + D_i(t)^{\ 2}};\ \ i=1, 2, 3 \qquad \text{(Eq B.6)}$$

If the vehicle is assumed to travel at accelerating speed toward $x = x_3$ (closest CPA), the velocity at CPA is:

$$v_3 = a_o t_3 \tag{Eq B.7}$$

Therefore, Equation B.6 is, for $(0 \leq t \leq t_3)$,

$$R_3(t) = \sqrt{d_3^{\ 2} + [\ v_3(t_3 - t) - \frac{a_o}{2}(t_3 - t)^2\ ]^2} \tag{Eq B.8}$$

If the vehicle is assumed to continue to accelerate after passing x_3 but reaches a final speed, v_m, before passing the next sound level meter at x_2, the final vehicle speed is:

$$v_m = a_o t_m \tag{Eq B.9}$$

where t_m= time at which the vehicle reaches final speed.

The slant distance between the vehicle and M3 during this intermediate time interval is, for $(t_3 < t \leq t_m)$,

$$R_3(t) = \sqrt{d_3^{\ 2} + [\ v_m(t_3 - t) - \frac{a_o}{2}(t_m - t)^2\ ]^2} \tag{Eq B.10}$$

After the vehicle has reached its steady roadway speed, its velocity remains constant as it passes the second and third sound level meters. Thus, the slant distance between the vehicle and M3 is, for $(t > t_m)$,

$$R_3(t) = \sqrt{d_3^{\ 2} + (v_m(t_3 - t))^2} \tag{Eq B.11}$$

In the actual vehicle acceleration noise test performed, the vehicle was noted to reach its final speed between x_3 and x_2. Therefore, the slant distance equations for M2 and M1 are similar to those for M3 but involve only the time interval conditions stated for $t_3 < t \leq t_m$ and $t > t_m$. Therefore, the slant distance equations for M2 and M1, respectively, are:

For $(0 \le t \le t_m)$,

$$R_2(t) = \sqrt{d_2^{\ 2} + [\, v_m (t_2 - t) - \frac{a_o}{2} (t_2 - t)^2 \,]^2} \qquad \text{(Eq B.12)}$$

$$R_1(t) = \sqrt{d_1^{\ 2} + [\, v_m (t_1 - t) - \frac{a_o}{2} (t_1 - t)^2 \,]^2} \qquad \text{(Eq B.13)}$$

For $(t > t_m)$,

$$R_2(t) = \sqrt{d_2^{\ 2} + (v_m \ (t_2 - t))^2} \qquad \text{(Eq B.14)}$$

$$R_1(t) = \sqrt{d_1^{\ 2} + (v_m \ (t_1 - t))^2} \qquad \text{(Eq B.15)}$$

The time-dependent sound level observed at each sound level meter is expressed by:

$$A_i(t) = 20 \log \left[10^{\frac{60.5}{20}} + 10^{\frac{L_i}{20}} \frac{1}{R_i(t)} \right] \qquad i = 1, 2, 3 \qquad \text{(Eq B.16)}$$

where the background noise level observed during the actual field tests was 60.5dBA and L_i is the reference source noise level of the vehicle (dBA at 1 m).

APPENDIX C

TRAFFIC NOISE FIELD DATA — FM 3009

APPENDIX C

TRAFFIC NOISE FIELD DATA — FM 3009

Appendix C presents a complete record of traffic noise field measurements collected on FM 3009 at Greenfield Village Subdivision, Schertz, Texas. These records include the position coordinates of the sound level meter locations, microphone calibration data, and average sound level readings for each 10-minute noise recording time interval. The noise readings are processed to take into account the microphone sensitivity calibrations and to normalize the average sound levels for noise contour mapping and comparison to each other.

Tables C.1 through C.6 list the field coordinates for each of the sound level meter location points. A secondary coordinate system was devised for convenient layout of the microphone stations along the residential streets. The coordinate system used the left curb facing toward FM 3009 as the reference axis. Lines perpendicular to this curb were used to locate the microphone stations and the set-back distances of the houses, garages, fences, etc. Microphone stations to the left of the reference curb were given negative coordinates in the x-direction. Column headings with an M followed by the letter R or a number between 1 and 3 denote the reference microphone and the other three microphones. The columns are subdivided into coordinate columns and a Metrosonics program data file column.

Table C.7 presents the microphone calibration data. The first column lists the microphones, designated by their corresponding serial numbers. The Metrosonics program data file numbers are also included in the table. The sensitivity corrections adjust microphones one through three to the reference microphone.

Tables C.8 through C.15 list the sound level meter readings by site location, recording time, microphone calibration adjustment, and sound-referenced normalization adjustment at each station. The second column, labeled “Reading,” is the raw noise level measurement obtained from the sound level meter. The “Calibration Adjustment” column presents the sensitivity corrections used to adjust readings before normalization.

Table C.1 Sound Level Meter Positions and Data Files for Cyrus McCormick Street

Street Address	Date	Time	Group	M-R		M-1		M-2		M-3	
	(1996)	(24-hr)		(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File
1200 Cyrus McCormick	May 17	0640	1	(19,0)	517AM 31001	(0,7)	517AM 31004	(40,0)	517AM 31007	(0,37)	517AM 310010
	May 17	0652	2	(19,0)	517AM 31002	(19,30)	517AM 31005	(40,0)	517AM 31008	(40,30)	517AM 310011
1204 Cyrus McCormick	May 17	0730	3	(19,0)	517AM 310013	(19,60)	517AM 310015	(40,60)	517AM 310017	(-11,50)	517AM 310019
	May 17	0750	4	(19,0)	517AM 310014	(19,90)	517AM 310016	(40,90)	517AM 310018	(-11,80)	517AM 310020
	May 17	1630	5	(19,0)	517PM 31001	(19,120)	517PM 31003	(40,120)	517PM 31005	(-11,110)	517PM 31007
	May 17	1644	6	(19,0)	517PM 31002	(19,142)	517PM 31004	(19,176)	517PM 31006	(-11,176)	517PM 31008
1205 Cyrus McCormick	May 17	1710	7	(19,0)	517PM 31009	(65,0)	517PM 310011	(96,8)	517PM 310013	(65,30)	517PM 310015
	May 17	1722	8	(19,0)	517PM 310010	(75,69)	517PM 310012	(75,39)	517PM 310014	(65,60)	517PM 310016
1209 Cyrus McCormick	May 17	1750	9	(19,0)	517PM 310017	(75,99)	517PM 310020	(65,90)	517PM 310023	(65,120)	517PM 310026
	May 17	1802	10	(19,0)	517PM 310018	(75,123)	517PM 310021	(65,145)	517PM 310024	(75,159)	517PM 310028
1200 Cyrus McCormick	July 10	0856	11	(19,0)	710AM 310035	(37,30)	710AM 310037	(19,30)	710AM 310039	(0,30)	710AM 310041
1205 Cyrus McCormick	July 10	0918	12	(19,0)	710AM 310042	(55,0)	710AM 310044	(55,30)	710AM 310046	(90,0)	710AM 310048
1204 Cyrus McCormick	July 10	0951	13	(19,0)	710AM 310043	(19,60)	710AM 310045	(37,60)	710AM 310047	(0,65)	710AM 310049

Table C.2 Sound Level Meter Positions and Data Files for Will Rogers Street

Street Address	Date	Time	Group	M-R		M-1		M-2		M-3	
	(1996)	(24-hr)		(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File
145 Will Rogers	May 20	0640	1	(24,0)	520AM 31001	(42,0)	520AM 31003	(20,30)	520AM 31005	(40,30)	520AM 31007
	May 20	0654	2	(24,0)	520AM 31002	(0,30)	520AM 31004	(-7,10)	520AM 31006	(39,30)	520AM 31008
	May 20	0715	3	(24,0)	520AM 31009	(11,56)	520AM 310012	(-7,66)	520AM 310015	(34,60)	520AM 310018
	May 20	0728	4	(24,0)	520AM 310010	(11,86)	520AM 310013	(-7,96)	520AM 310016	(31,90)	520AM 310019
	May 20	0755	5	(24,0)	520AM 310021	(11,116)	520AM 310023	(-7,126)	520AM 310025	(31,120)	520AM 310027
141 Will Rogers	May 20	0808	6	(24,0)	520AM 310022	(11,146)	520AM 310024	(-7,156)	520AM 310026	(31,150)	520AM 310028
	May 20	0830	7	(24,0)	520AM 310029	(14,176)	520AM 310032	(-7,186)	520AM 310035	(34,180)	520AM 310038
	May 20	0842	8	(24,0)	520AM 310030	(21,206)	520AM 310033	(-7,216)	520AM 310036	(39,210)	520AM 310039
	May 20	1650	9	(24,0)	520PM 31001	(59,0)	520PM 31003	(55,30)	520PM 31005	(89,0)	520PM 31007
	May 20	1702	10	(24,0)	520PM 31002	(119,21)	520PM 31004	(89,0)	520PM 31006	(119,0)	520PM 31008
	May 20	1725	11	(24,0)	520PM 31009	(89,30)	520PM 310011	(207,43)	520PM 310013	(52,60)	520PM 310015
137 Will Rogers	May 20	1738	12	(24,0)	520PM 310010	(89,60)	520PM 310012	(50,120)	520PM 310014	(50,90)	520PM 310016
	May 20	1800	13	(24,0)	520PM 310017	(80,120)	520PM 310021	(50,120)	520PM 310023	(50,150)	520PM 310026
	May 20	1815	14	(24,0)	520PM 310020	(79,215)	520PM 310022	(50,180)	520PM 310024	(59,210)	520PM 310027

Table C.3 Sound Level Meter Positions and Data Files for Cherrywood Street

Street Address	Date	Time	Group	M-R		M-1		M-2		M-3	
	(1996)	(24-hr)		(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File
1200 Cherrywood	May 22	0630	1	(11,0)	522AM 31001	(-19,20)	522AM 31004	(-4,10)	522AM 31007	(30,0)	522AM 310010
	May 22	0644	2	(11,0)	522AM 31002	(-19,56)	522AM 31005	(-4,38)	522AM 31008	(30,0)	522AM 310011
	May 22	0710	3	(11,0)	522AM 310013	(15,61)	522AM 310016	(15,30)	522AM	(30,30)	522AM 310019
1204 Cherrywood	May 22	0722	4	(11,0)	522AM 310015	(15,91)	522AM 310018	(-19,86)	522AM	(30,60)	522AM 310020
	May 22	0800	5	(11,0)	522AM 310021	(42,90)	522AM 310023		522AM	(15,125)	522AM 310026
1206 Cherrywood	May 22	0813	6	(11,0)	522AM 310022	(15,150)	522AM 310024	(-19,123)	522AM	(-19,153)	522AM 310027
	May 22	0840	7	(11,0)	522AM 310028	(15,76)	522AM 310031	(-19,86)	522AM 310034	(15,99)	522AM 310038
1201 Cherrywood	May 22	0854	8	(11,0)	522AM 310029	(64,14)	522AM 310032	(104,14)	522AM 310035	(49,14)	522AM 310039
	May 22	1635	9	(11,0)	522PM 31001	(85,44)	522PM 31004	(62,44)	522PM 31007	(49,44)	522PM 310010
1205 Cherrywood	May 22	1650	10	(11,0)	522PM 31003	(70,75)	522PM 31006	(53,74)	522PM 31009	(85,74)	522PM 310012
	May 22	1715	11	(11,0)	522PM 310013	(70,99)	522PM 310015	(53,104)	522PM 310018	(85,104)	522PM 310020
1207 Cherrywood	May 22	1755	12	(11,0)	522PM 310014	(87,105)	522PM 310017	(83,104)	522PM 310019	(85,134)	522PM 310021
	May 22	1727	13	(11,0)	522PM 310022	(97,135)	522PM 310024	(83,134)	522PM 310026	(85,164)	522PM 310028
1201 Cherrywood	July 10	640	14	(11,0)	710AM 31009	(30,0)	710AM 310011	(48,0)	710AM 310013	(66,10)	710AM 310015
	July10	652	15	(11,0)	710AM 310010	(30,30)	710AM 310012	(48,30)	710AM 310014	(66,45)	710AM 310017
	July 10	715	16	(11,0)	710AM 310018	(30,60)	710AM 310020	(48,60)	710AM 310022	(74,75)	710AM 310024
1205 Cherrywood	July 10	727	17	(11,0)	710AM 310019	(30,90)	710AM 310021	(48,90)	710AM 310023	(74,105)	710AM 310025
	July 10	750	18	(11,0)	710AM 310026	(30,120)	710AM 310028	(48,120)	710AM 310030	(68,135)	710AM 310032
1207 Cherrywood	July 10	802	19	(11,0)	710AM 310027	(30,150)	710AM 310029	(48,150)	710AM 310031	(68,165)	710AM 310033
1206 Cherrywood	July 10	830	20	(11,0)	710AM 310034	(-20,132)	710AM 310036	(4,132)	710AM 310038	(15,164)	710AM 310040

Table C.4 Sound Level Meter Positions and Data Files for the Utility Access Alley

Street Address	Date	Time	Group	M-R		M-1		M-2		M-3	
	(1996)	(24-hr)		(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File
ALLEY	May 22	1817	1	(0,0)	522PM 310023	(0,60)	522PM 310025	(0,20)	522PM 310027	(0,40)	522PM 310029
ALLEY	May 22	1840	2	(0,20)	522PM 310030	(0,90)	522PM 310031	(0,120)	522PM 310032	(0,150)	522PM 310033

Table C.5 Sound Level Meter Positions and Data Files for behind the Barrier

Street Address	Date	Time	Group	M-R		M-1		M-2		M-3	
	(1996)	(24-hr)		(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File
BEHIND BARRIER	May 23	0655	1	(0,0,)	523AM 31001	(0,8)	523AM 31004	(0,30)	523AM 31009	(0,60)	523AM 310012
	May 23	0713	2	(0,0)	523AM 31002	(0,8)	523AM 31005	(0,30)	523AM 310010	(0,30,10)	523AM 310013
	May 23	0750	3	(0,0)	523AM 310015	(0,150)	523AM 310017	(0,90)	523AM 310019	**(0,120)**	523AM 310021

Table C.6 Sound Level Meter Positions and Data Files for the Open Field

Street Address	Date	Time	Group	M-R		M-1		M-2		M-3	
	(1996)	(24-hr)		(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File	(x,y)(ft)	File
OPEN FIELD	May 23	0811	1	(0,0)	523AM 310016	(0,CURB)	523AM 310018	(0,30)	523AM 310020	(0,60)	523AM 310022
	May 23	0840	2	(0,0)	523AM 310023	(0,90)	523AM 310024	(0,120)	523AM 310025	(0,150)	523AM 310026
	May 23	0910	3	(1854, CURB)	523AM 310027	(927, CURB)	523AM 310028	(618, CURB)	523AM 310030	(309, CURB)	523AM 310031

Table C.7 Microphone Sensitivity Calibration and Data Corrections

MICROPHONE (SERIAL #)	DATE (1996)	FILE	CALIBRATION (dBA)	SENSITIVITY CORRECTION
MR (#4881)	5-17 AM	31003	102.2	0 dBA
M1(#4873)	5-17 AM	31006	101.6	add 0.6 dBA
M2(#4838)	5-17 AM	31009	102.3	subtract 0.1 dBA
M3(#4874)	5-17 AM	310012	101.8	add 0.4 dBA
MR(#4881)	5-17 PM	310019	102.3	0 dBA
M1(#4873)	5-17 PM	310022	101.5	add 0.8 dBA
M2(#4838)	5-17 PM	310025	101.5	add 0.8 dBA
M3(#4874)	5-17 PM	310029	101.8	add 0.5 dBA
MR(#4881)	5-20 AM	310011	102.2	0 dBA
M1(#4873)	5-20 AM	310014	101.4	add 0.8 dBA
M2(#4838)	5-20 AM	310017	102.1	add 0.1 dBA
M3(#4874)	5-20 AM	310020	102.1	add 0.1 dBA
MR(#4881)	5-20 PM	310031	102.3	0 dBA
M1(#4873)	5-20 PM	310034	101.4	add 0.8 dBA
M2(#4838)	5-20 PM	310037	101.8	add 0.5 dBA
M3(#4874)	5-20 PM	310040	102.0	add 0..3 dBA
MR(#4881)	5-22 AM	31003	102.1	0 dBA
M1(#4873)	5-22 AM	31006	101.3	add 0.8 dBA
M2(#4838)	5-22 AM	31009	102.1	add 0. dBA
M3(#4874)	5-22 AM	310012	102.0	add 0.1 dBA
MR(#4881)	5-22 AM	310030	102.3	0 dBA
M1(#4873)	5-22 AM	310033	101.4	add 0.9 dBA
M2(#4838)	5-22 AM	310037	102.0	add 0.3 dBA
M3(#4874)	5-22 AM	310040	102.1	add 0.2 dBA
MR(#4881)	5-22 PM	31002	102.6	0 dBA
M1(#4873)	5-22 PM	31005	101.6	add 1.0 dBA
M2(#4838)	5-22 PM	31008	101.0	add 1.6 dBA
M3(#4874)	5-22 PM	310011	102.3	add 0.3 dBA
MR(#4881)	5-23 AM	31003	102.2	0 dBA
M1(#4873)	5-23 AM	31008	101.5	add 0.7 dBA
M2(#4838)	5-23 AM	310011	102.1	add 0.1 dBA
M3(#4874)	5-23 AM	310014	102.0	add 0.2 dBA
MR(#4881)	7-10 AM	310017	102.1	0 dBA
M1(#4873)	7-10 AM	310019	101.4	add 0.7 dBA
M2(#4838)	7-10 AM	310021	102.3	subtract 0.2 dBA
M3(#4874)	7-10 AM	310023	102.1	0 dBA
MR(#4881)	7-10 AM	310025	102.0	0 dBA
M1(#4873)	7-10 AM	310030	101.4	add 0.6 dBA
M2(#4838)	7-10 AM	310033	102.2	subtract 0.2 dBA
M3(#4874)	7-10 AM	310037	102.0	0 dBA

Table C. 8 Sound Level Measurements, Cyrus McCormick (5-17-96 a.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
1MR	69.9	0.0	69.9	0.0	69.9
1M1	63.4	0.6	64.0	0.0	64.0
1M2	69.9	-0.1	69.8	0.0	69.8
1M3	62.4	0.4	62.8	0.0	62.8
2MR	70.0	0.0	70.0	-0.1	69.9
2M1	60.5	0.6	61.6	-0.1	61.5
2M2	70.0	-0.1	69.9	-0.1	69.8
2M3	60.9	0.4	61.3	-0.1	61.2
3MR	70.7	0.0	70.7	-0.8	69.9
3M1	58.2	0.6	58.8	-0.8	58.0
3M2	59.1	-0.1	59.0	-0.8	58.2
3M3	60.2	0.4	60.6	-0.8	59.8
4MR	71.6	0.0	71.6	-1.7	69.9
4M1	58.5	0.6	59.1	-1.7	57.4
4M2	60.8	-0.1	60.7	-1.7	59.0
4M3	59.1	0.4	59.5	-1.7	57.8

Table C.9 Sound Level Measurements, Cyrus McCormick (5-17-96 p.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
5MR	77.1	0	77.1	0	77.1
5M1	59.9	0.8	60.7	0	60.7
5M2	64.7	0.8	65.5	0	65.5
5M3	60.7	0.5	61.2	0	61.2
6MR	81.8	0	81.8	-4.7	77.1
6M1	78.1	0.8	78.9	-4.7	74.2
6M2	77.1	0.8	77.9	-4.7	73.2
6M3	72.1	0.5	72.6	-4.7	67.9
7MR	76.3	0	76.3	0.8	77.1
7M1	67.4	0.8	68.2	0.8	69
7M2	69.6	0.8	70.4	0.8	71.2
7M3	69.1	0.5	69.6	0.8	70.4
8MR	**69.7**	0	69.7	7.4	77.1
8M1	56.1	0.8	56.9	7.4	64.3
8M2	56.9	0.8	57.7	7.4	65.1
8M3	54.8	0.5	55.3	7.4	62.7
9MR	69.8	0	69.8	7.3	77.1
9M1	54.7	0.8	55.5	7.3	62.8
9M2	53.9	0.8	54.7	7.3	62
9M3	54.2	0.5	54.7	7.3	62
10MR	68.3	0	68.3	8.8	77.1
10M1	52.1	0.8	52.9	8.8	61.7
10M2	51.6	0.8	52.4	8.8	61.2
10M3	52.6	0.5	53.4	8.8	62.2

Table C.10 Sound Level Measurements, Will Rogers (5-20-96 a.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
1MR	69.6	0	69.6	0	69.6
1M1	68.3	0.8	69.1	0	69.1
1M2	64.7	0.1	64.8	0	64.8
1M3	64.5	0.1	64.6	0	64.6
2MR	71.5	0	71.5	-1.9	69.6
2M1	64.9	0.8	65.7	-1.9	63.8
2M2	65.7	0.1	65.8	-1.9	63.9
2M3	66.6	0.1	66.7	-1.9	64.8
3MR	72.5	0	72.5	-2.9	69.6
3M1	64.4	0.8	65.2	-2.9	62.3
3M2	64.9	0.1	65	-2.9	62.1
3M3	65.8	0.1	65.9	-2.9	63
4MR	70.2	0	70.2	-0.6	69.6
4M1	58.4	0.8	59.2	-0.6	58.6
4M2	60.8	0.1	60.9	-0.6	60.3
4M3	61.3	0.1	61.4	-0.6	60.8
5MR	71.2	0	71.2	-1.6	69.6
5M1	59.3	0.8	60.1	-1.6	58.5
5M2	59.6	0.1	59.7	-1.6	58.1
5M3	60.7	0.1	60.8	-1.6	59.2
6MR	70.5	0	70.5	-0.9	69.6
6M1	57	0.8	57.8	-0.9	56.9
6M2	57.7	0.1	57.8	-0.9	56.9
6M3	58.1	0.1	58.2	-0.9	57.3
7MR	70.6	0	70.6	-1	69.6
7M1	56.7	0.8	57.5	-1	56.5
7M2	57.4	0.1	57.5	-1	56.5
7M3	57.1	0.1	57.2	-1	56.2
8MR	71	0	71	-1.4	69.6
8M1	57.8	0.8	58.6	-1.4	57.2
8M2	58.2	0.1	58.3	-1.4	56.9
8M3	57.6	0.1	57.7	-1.4	56.3

Table C.11 Sound Level Measurements, Will Rogers (5-20-96 p.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
9MR	70.6	0	70.6	-1	69.6
9M1	68.9	0.9	69.8	-1	68.8
9M2	65.7	0.5	66.2	-1	65.2
9M3	62.9	0.3	63.2	-1	62.2
10MR	70.3	0	70.3	-0.7	69.6
10M1	57.9	0.9	58.8	-0.7	58.1
10M2	58.4	0.5	58.9	-0.7	58.2
10M3	57.1	0.3	57.4	-0.7	56.7
11MR	70.5	0	70.5	-0.9	69.6
11M1	64.4	0.9	65.3	-0.9	64.4
11M2	-----	-----	-----NOT	OPERATED-----	-----
11M3	65.4	0.3	65.7	-0.9	64.8
12MR	70	0	70	-0.4	69.6
12M1	61.5	0.9	62.4	-0.4	62
12M2	-----	-----	-----NOT	OPERATED-----	-----
12M3	61.9	0.3	62.2	-0.4	61.8
13MR	69.6	0	69.6	0	69.6
13M1	59.6	0.9	57.8	0	57.8
13M2	59	0.5	59.5	0	59.5
13M3	57.9	0.3	58.2	0	58.2
14MR	68.4	0.9	68.4	1.2	69.6
14M1	50.3	0.5	51.2	1.2	52.4
14M2	55.4	0.3	55.9	1.2	57.1
14M3	55.2	0.3	55.5	1.2	56.7

Table C.12 Sound Level Measurements, Cherrywood (5-20-96 a.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
1MR	69.9	0.0	69.9	0.0	69.9
1M1	59.2	0.8	60.0	0.0	60.0
1M2	64.5	0.0	64.5	0.0	64.5
1M3	69.6	0.1	69.7	0.0	69.7
2MR	70.3	0.0	70.3	-0.4	69.9
2M1	58.4	0.8	59.2	-0.4	58.8
2M2	61.2	0.0	61.2	-0.4	60.8
2M3	69.7	0.1	69.8	-0.4	69.4
3MR	71.7	0.0	71.7	-1.8	69.9
3M1	61.5	0.8	62.3	-1.8	60.5
3M2	-------------	--------------------	--------NOT	OPERATED----	--------------------
3M3	66.6	0.1	66.7	-1.8	64.9
4MR	70.0	0.0	70.0	-0.1	69.9
4M1	56.4	0.8	57.2	-0.1	57.1
4M2	-------------	--------------------	--------NOT	OPERATED----	--------------------
4M3	59.3	0.1	59.4	-0.1	59.3
5MR	71.4	0.0	71.4	-1.5	69.9
5M1	56.6	0.8	57.4	-1.5	55.9
5M2	-------------	--------------------	--------NOT	OPERATED----	--------------------
5M3	54.3	0.1	54.4	-1.5	52.9
6MR	70.3	0.0	70.3	-0.4	69.9
6M1	57.4	0.9	58.3	-0.4	57.9
6M2	-------------	--------------------	--------NOT	OPERATED----	--------------------
6M3	53.9	0.2	54.1	-0.4	53.7
7MR	69.9	0.0	69.9	0.0	69.9
7M1	56.6	0.9	57.5	0.0	57.5
7M2	56.1	0.3	56.4	0.0	56.4
7M3	56.6	0.2	56.8	0.0	56.8
8MR	69.9	0.0	69.9	0.0	69.9
8M1	65.3	0.9	66.2	0.0	66.2
8M2	63.1	0.3	63.4	0.0	63.4
8M3	67.7	0.2	67.9	0.0	67.9

Table C.13 Sound Level Measurements, Cherrywood (5-22-96 p.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
9MR	70.2	0.0	70.2	-0.3	69.9
9M1	58.5	1.0	59.5	-0.3	59.2
9M2	60.2	1.6	61.8	-0.3	61.5
9M3	61.0	0.3	61.3	-0.3	61.0
10MR	69.0	0.0	69.0	0.9	69.9
10M1	56.2	1.0	57.2	0.9	57.1
10M2	57.9	1.6	59.5	0.9	60.4
10M3	56.7	0.3	57.0	0.9	57.9
11MR	69.3	0.0	69.3	0.6	69.9
11M1	56.2	1.0	57.2	0.6	57.8
11M2	57.9	1.6	59.5	0.6	60.1
11M3	60.1	0.3	60.4	0.6	61.0
12MR	70.8	0.0	70.8	-0.9	69.9
12M1	52.1	1.0	53.1	-0.9	52.2
12M2	54.9	1.6	56.5	-0.9	55.6
12M3	53.2	0.3	53.5	-0.9	52.6
13MR	69.1	0.0	69.1	0.9	69.9
13M1	52.5	1.0	53.5	0.9	54.3
13M2	54.2	1.6	55.8	0.9	56.6
13M3	56.8	0.3	57.1	0.9	58.0
14MR	72.2	0.0	72.2	0.0	72.2
14M1	60.2	0.8	61.0	0	61.0
14M2	68.9	0.0	68.9	0.0	68.9
14M3	65.3	0.1	65.4	0.0	65.4
15MR	72.2	0.0	72.2	0.0	72.2
15M1	56.7	0.8	57.5	0.0	57.5
15M2	56.1	0.0	56.1	0.0	56.1
15M3	55.5	0.1	55.6	0.0	55.6

Table C.14 Sound Level Measurements, Robert Derrick (5-23-96 a.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
1MR	70.8	0.0	70.8	0.0	70.8
1M1	58.0	0.7	58.7	0.0	58.7
1M2	60.9	0.1	61.0	0.0	61.0
1M3	59.0	0.2	59.2	0.0	59.2
2MR	70.7	0.0	70.7	0.1	70.8
2M1	57.3	0.7	58.0	0.1	58.1
2M2	60.9	0.1	61.0	0.1	61.1
2M3	66.6	0.2	66.8	0.1	66.9
3MR	71.0	0.0	71.0	-0.2	70.8
3M1	59.3	0.7	60.0	-0.2	69.8
3M2	57.1	0.1	57.2	-0.2	57.0
3M3	58.5	0.2	58.7	-0.2	58.5
4MR	70.3	0.0	70.3	0.5	70.8
4M1	72.7	0.7	73.4	0.5	73.9
4M2	65.5	0.1	65.6	0.5	66.1
4M3	63.3	0.2	63.5	0.5	64.0
5MR	69.5	0.0	69.5	1.3	70.8
5M1	61.0	0.7	61.7	1.3	62.0
5M2	60.3	0.1	60.4	1.3	61.7
5M3	60.1	0.2	60.3	1.3	61.6
6MR	71.4	0.0	71.4	-0.6	70.8
6M1	73.6	0.7	74.3	-0.6	73.7
6M2	75.6	0.1	75.7	-0.6	75.1
6M3	75.8	0.2	76.0	-0.6	75.4

NOTES: (1) GR1 - GR3 behind barrier on Robert Derrick Street
(2) GR4 - GR6 in open field on FM 3009 opposite Robert Derrick Street test site.

Table C.15 Sound Level Measurements, Cherrywood (7-10-96 a.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
1MR	68.9	0.0	68.9	0.0	68.9
1M1	68.7	0.7	69.4	0.0	69.4
1M2	69.7	-0.2	69.5	0.0	69.5
1M3	63.6	0.0	63.6	0.0	63.6
2MR	69.5	0.0	69.5	-0.6	68.9
2M1	62.8	0.7	63.5	-0.6	62.9
2M2	62.6	-0.2	62.4	-0.6	61.8
2M3	60.2	0.0	60.2	-0.6	59.6
3MR	71.0	0.0	71.0	-2.1	68.9
3M1	59.8	0.7	60.5	-2.1	58.4
3M2	60.2	-0.2	60.0	-2.1	57.9
3M3	59.0	0.0	59.0	-2.1	56.9
4MR	69.9	0.0	69.9	-1.0	68.9
4M1	57.0	0.7	57.7	-1.0	56.7
4M2	57.7	-0.2	57.5	-1.0	56.5
4M3	55.2	0.0	55.2	-1.0	54.2
5MR	70.9	0.0	70.9	0.0	70.9
5M1	55.3	0.6	55.9	0.0	55.9
5M2	55.7	-0.2	55.5	0.0	55.5
5M3	56.4	0.0	56.4	0.0	56.4
6MR	70.5	0.0	70.5	0.4	70.9
6M1	53.5	0.6	54.1	0.4	54.5
6M2	55.3	-0.2	55.1	0.4	55.5
6M3	54.1	0.0	54.1	0.4	54.5
7MR	68.5	0.0	68.5	2.4	70.9
7M1	54.8	0.6	55.4	2.4	57.8
7M2	60.2	-0.2	60.0	2.4	62.4
7M3	58.0	0.0	58.0	2.4	60.4

Table C.16 Sound Level Measurements, Cyrus McCormick (7-10-96 a.m.)

MICROPHONE STATION	READING (dBA)	CALIBRATION ADJUSTMENT (dB)	ADJUSTED READING (dBA)	NORMALIZE TO REFERENCE MICROPHONE (dB)	NORMALIZED READING (dBA)
11MR	69.	0.0	69.1	0.8	69.9
11M1	61.5	0.6	62.1	0.8	62.9
11M2	62.1	-0.2	61.9	0.8	62.7
11M3	61.4	0.0	61.4	0.8	62.2
12MR	67.6	0.0	67.6	2.3	69.9
12M1	66.4	0.6	67.0	2.3	69.3
12M2	59.9	-0.2	59.7	2.3	62.0
12M3	59.5	0.0	59.5	2.3	61.8
13MR	66.9	0.0	66.9	3.0	69.9
13M1	55.9	0.6	56.5	3.0	59.5
13M2	57.1	-0.2	56.9	3.0	59.9
13M3	57.5	0.0	57.5	3.0	60.5

APPENDIX D

REFERENCES

APPENDIX D

REFERENCES

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